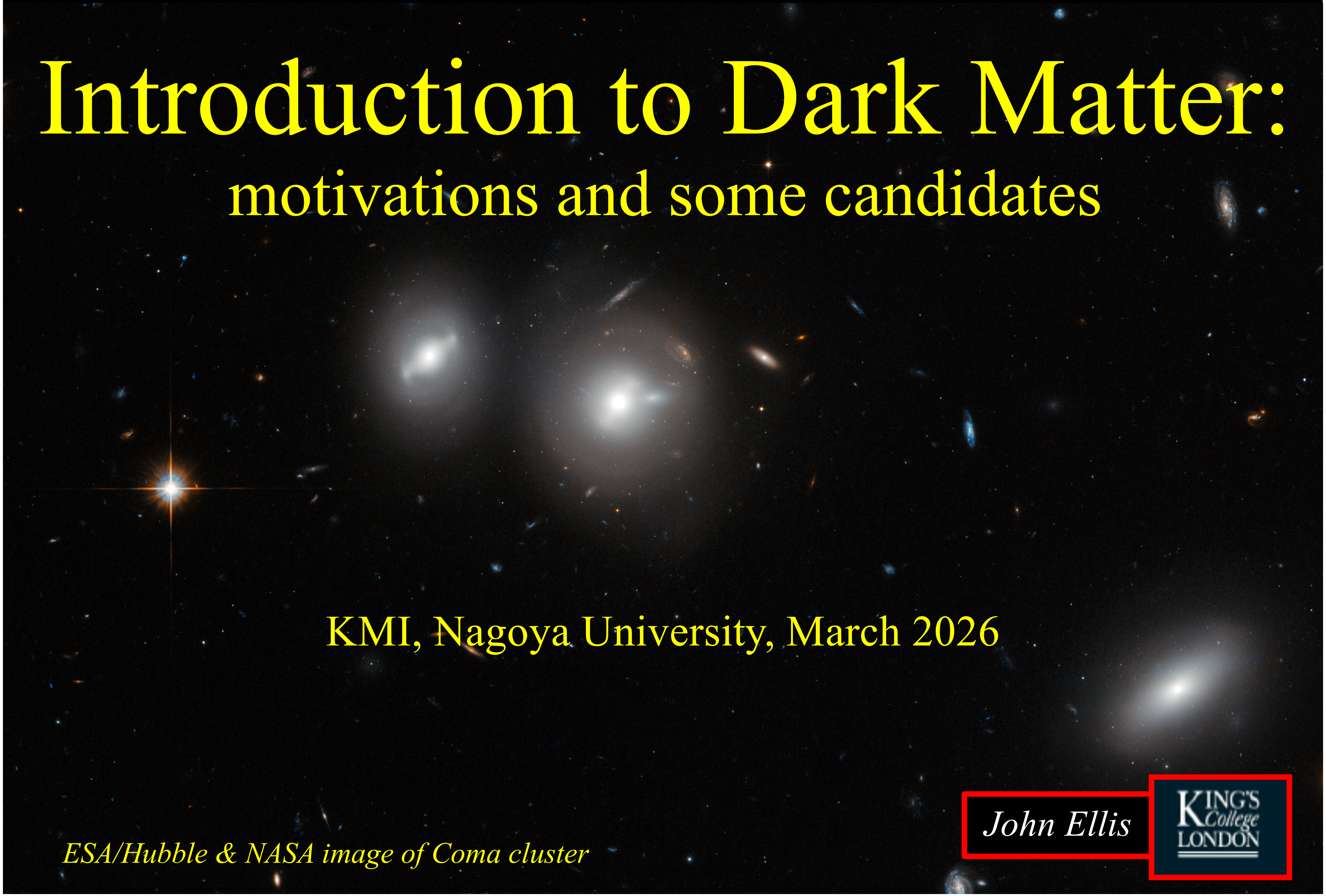
Introduction to Dark Matter:

motivations and some candidates

KMI, Nagoya University, March 2026

John Ellis

KING'S College LONDON



ESA/Hubble & NASA image of Coma cluster

Motivations for Dark Matter

- Excess velocities of galaxies and stars: rotation curves
- Structure formation
  - Growth of perturbations seen in CMB needs cold dark matter
- Cosmology
  - Pattern of temperature fluctuations measured in CMB, baryon acoustic perturbations (BAOs), …

Modified gravity cannot explain structure formation, nor cosmological measurements, in conflict with measurements of wide binary stars

The Dark Matter Hypothesis

- Proposed by Fritz Zwicky, based on observations of the Coma galaxy cluster
- The galaxies move too quickly to be held together
- The observations require a stronger gravitational field than provided by the visible matter
- **Dark matter?**

The Rotation Curves of Galaxies

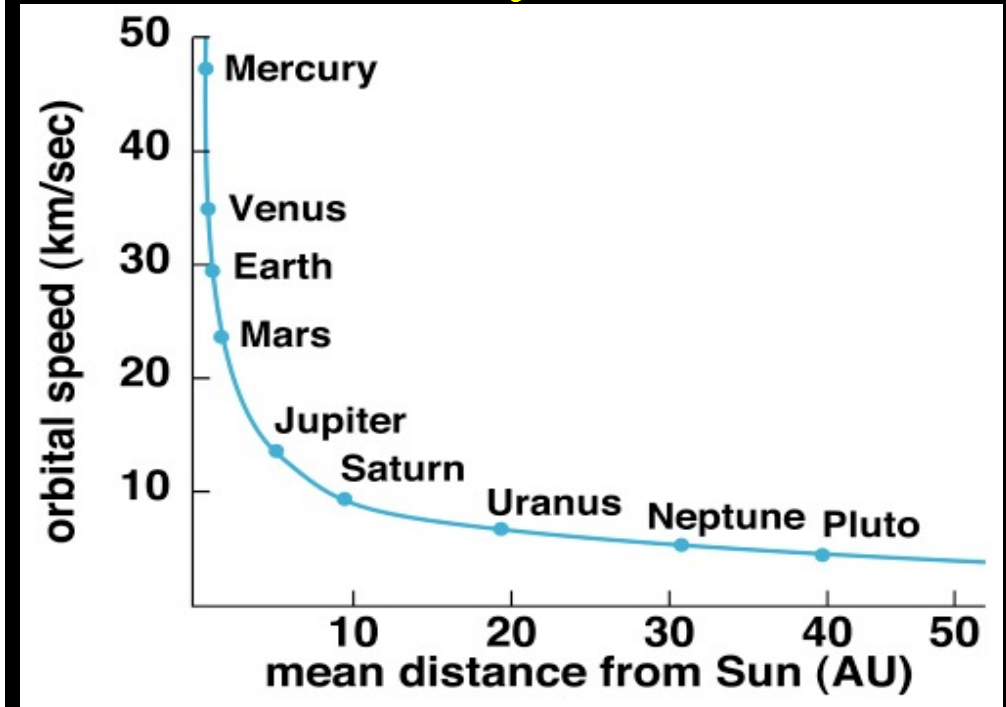
- Measured by Vera Rubin
- The stars also orbit 'too quickly'
- Her observations also required a stronger gravitational field than provided by the visible matter

Scanned at the American Institute of Physics

- **Further strong evidence for dark matter**
- Also:
  – Structure formation, cosmic background radiation, …

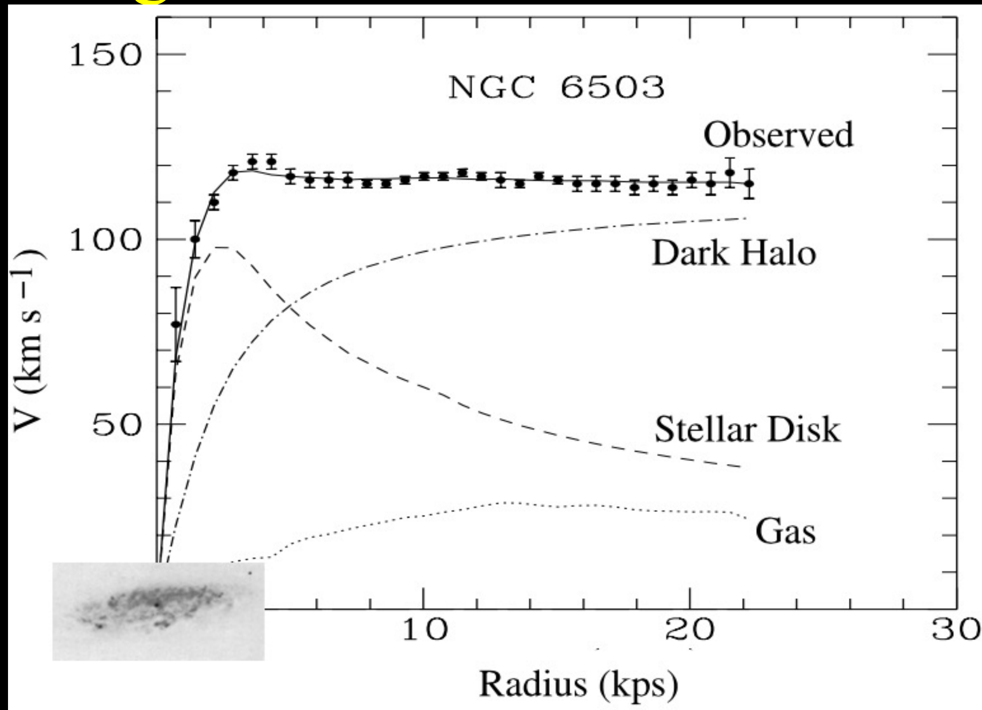
Galactic Rotation Curves

- In the Solar System



- The velocities decrease with distance from Sun
- Mass lumped at centre

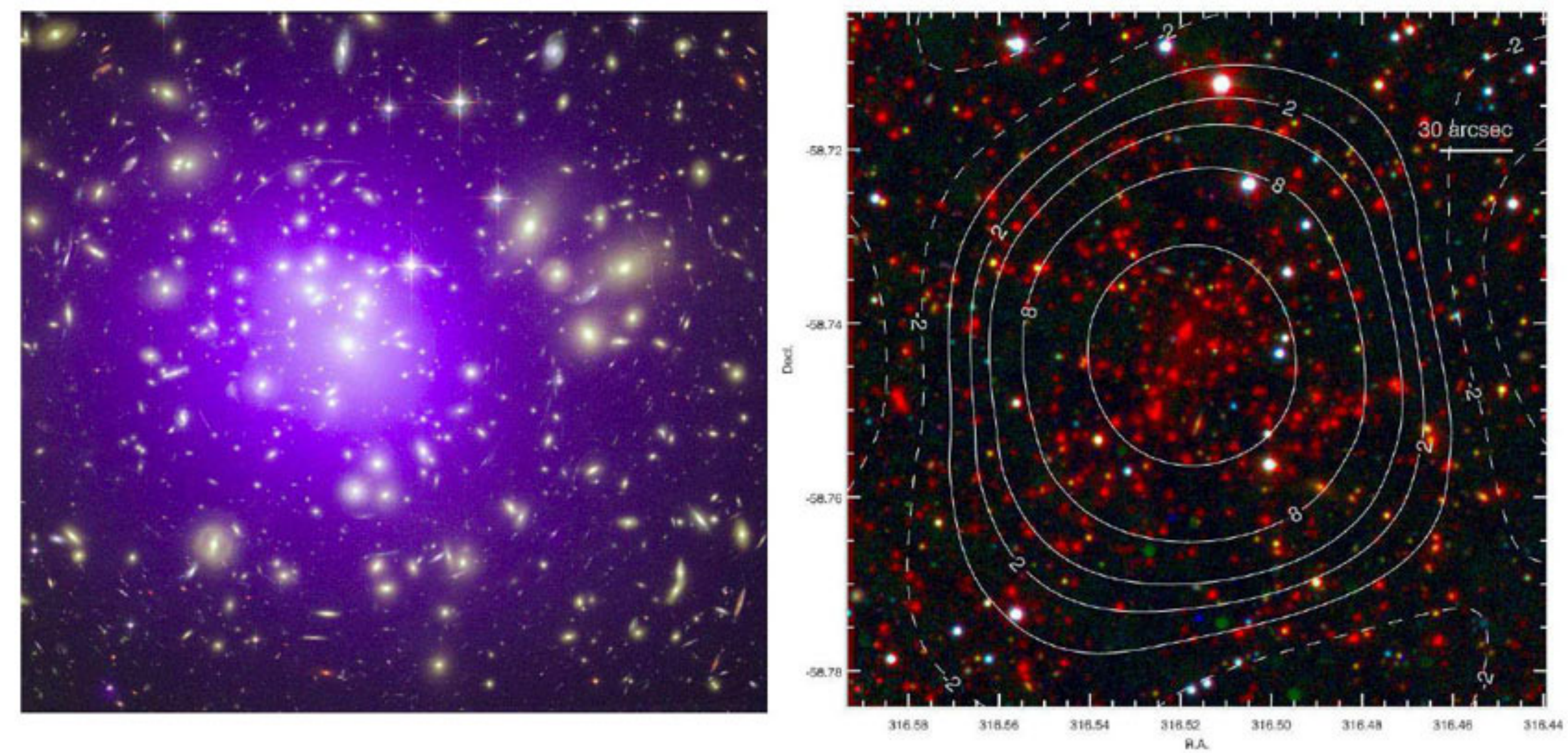
- In galaxies



- The velocities do not decrease with distance
- Dark matter spread out

X-Rays from Galaxy Clusters

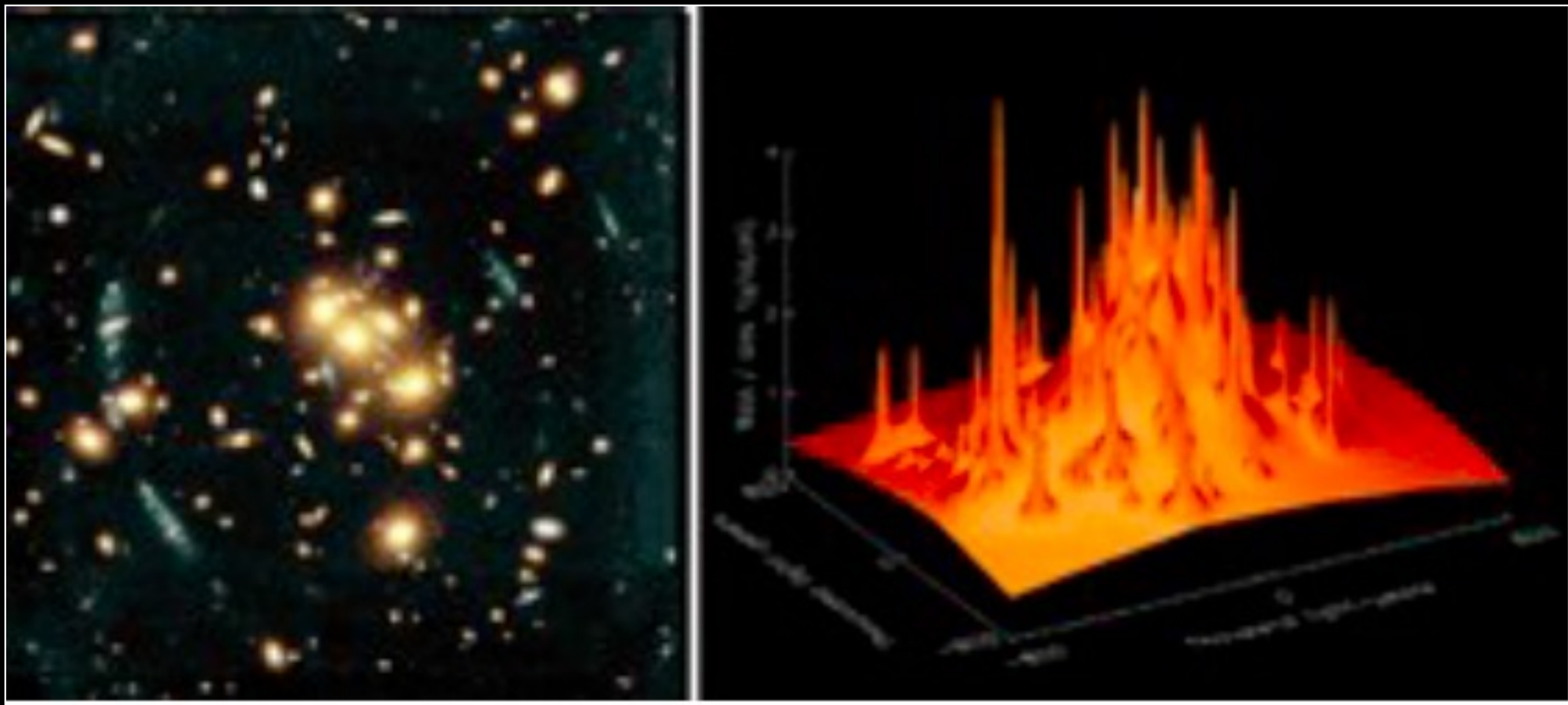
- Gas clouds at high temperature and pressure



- Need extra gravity to hold them together

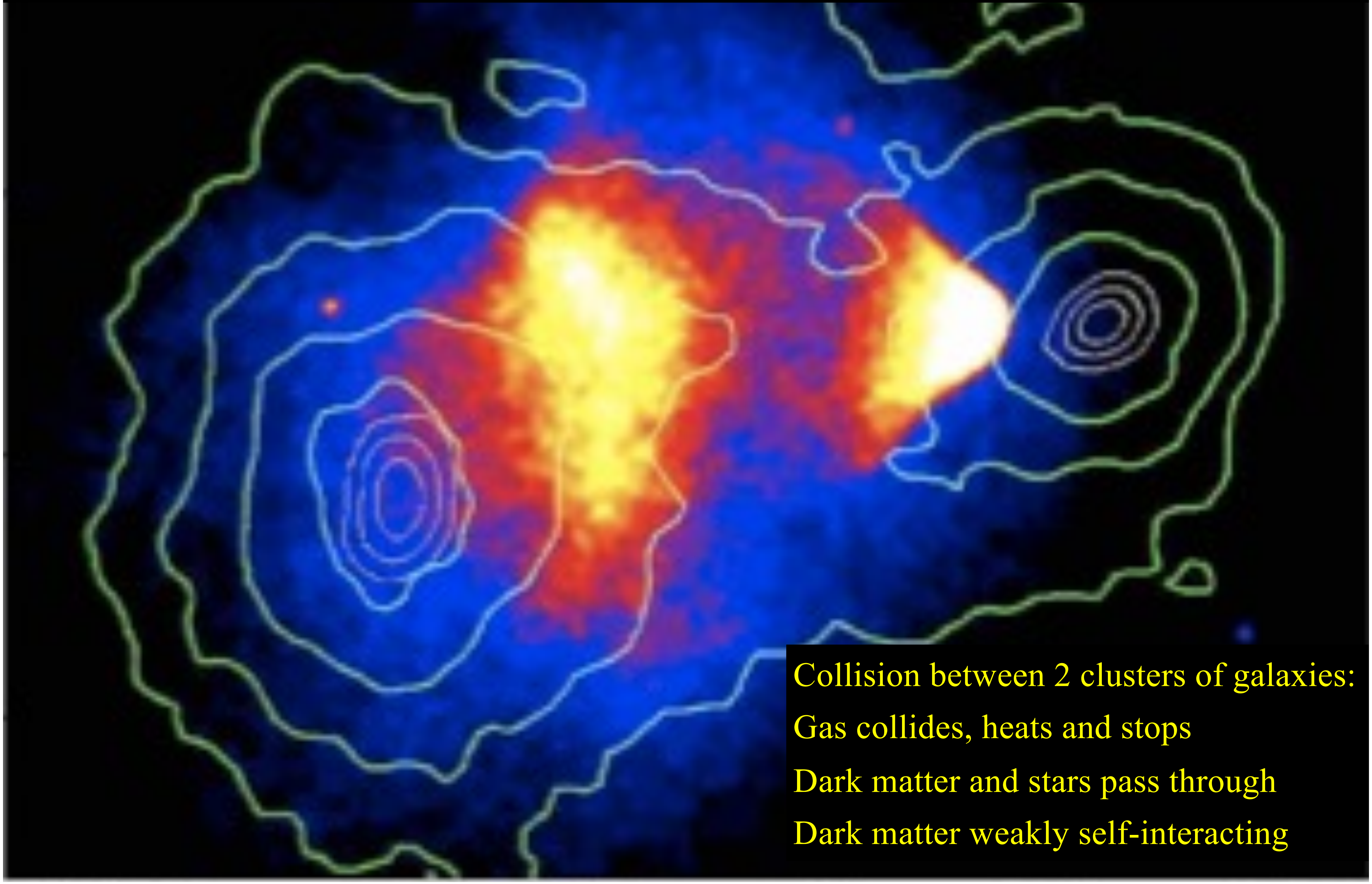
Gravitational Lensing

- Reveals all the matter



- Galaxies = peaks on a background of dark matter

Biggest Collider in the Universe?



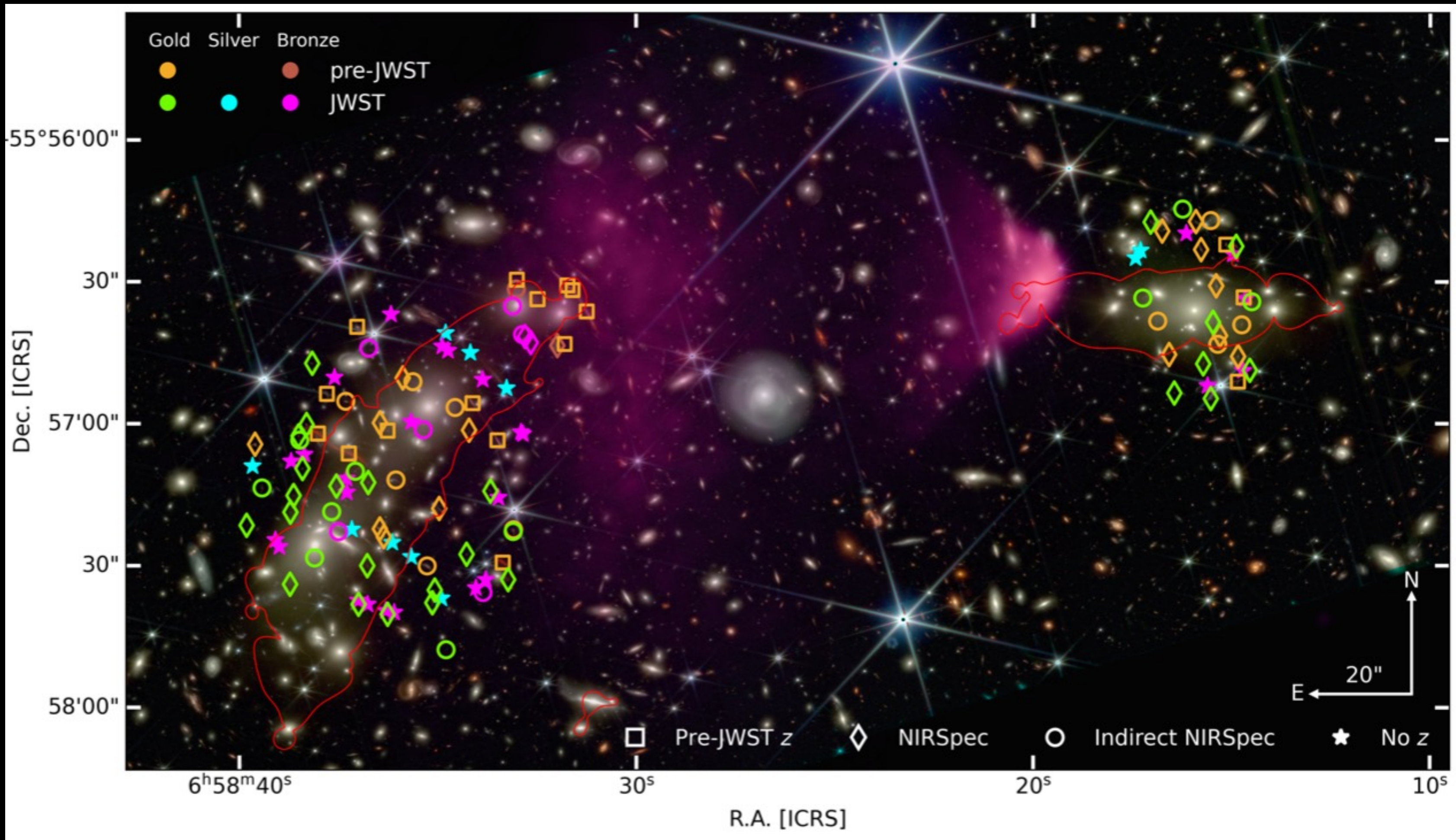
Collision between 2 clusters of galaxies:

Gas collides, heats and stops

Dark matter and stars pass through

Dark matter weakly self-interacting

JWST Study of Bullet Cluster

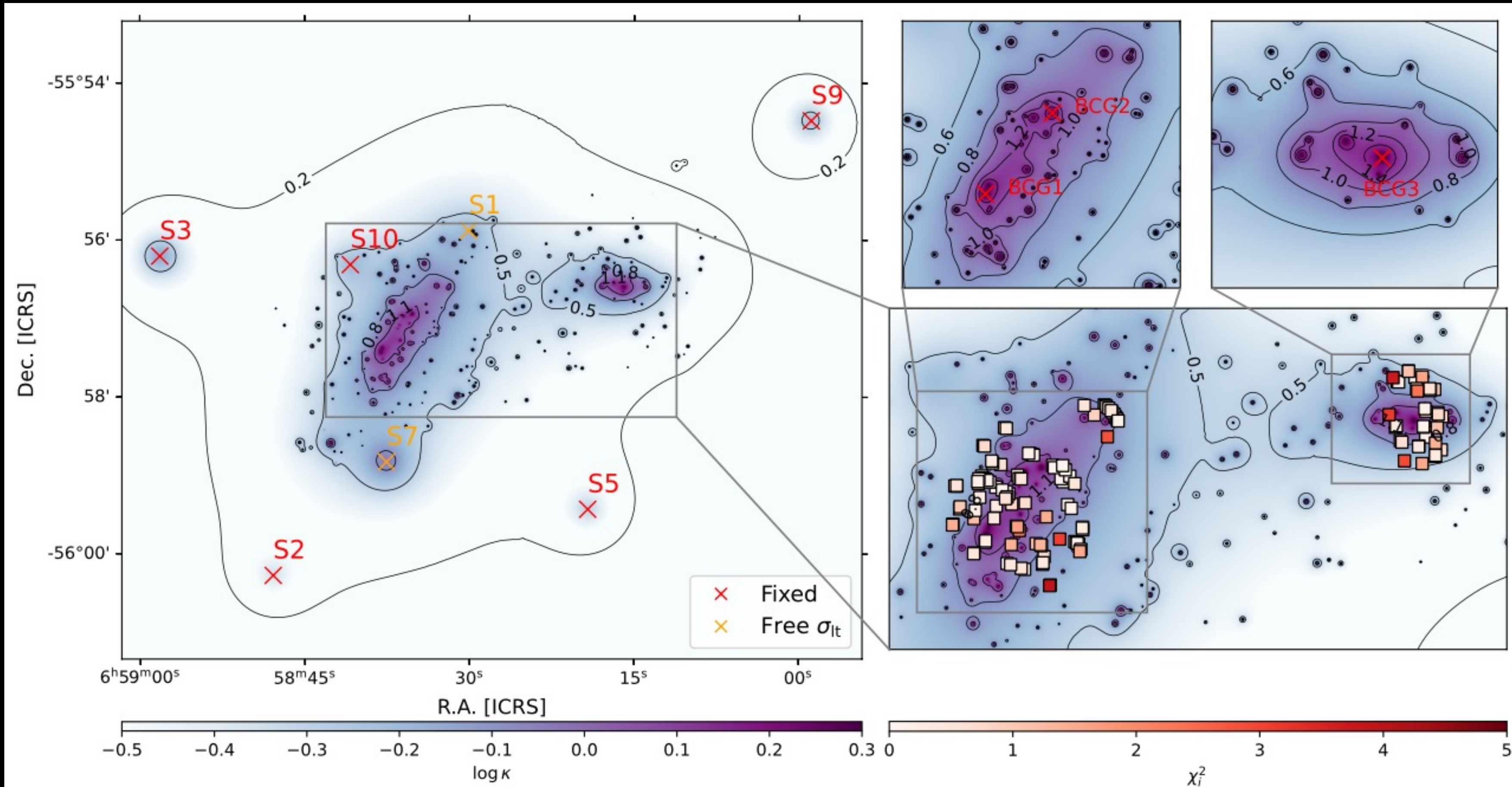


Pink shading shows hot gas

Symbols represent lensed background systems used to map density profile

Riharšič et al, arXiv:2601.22245

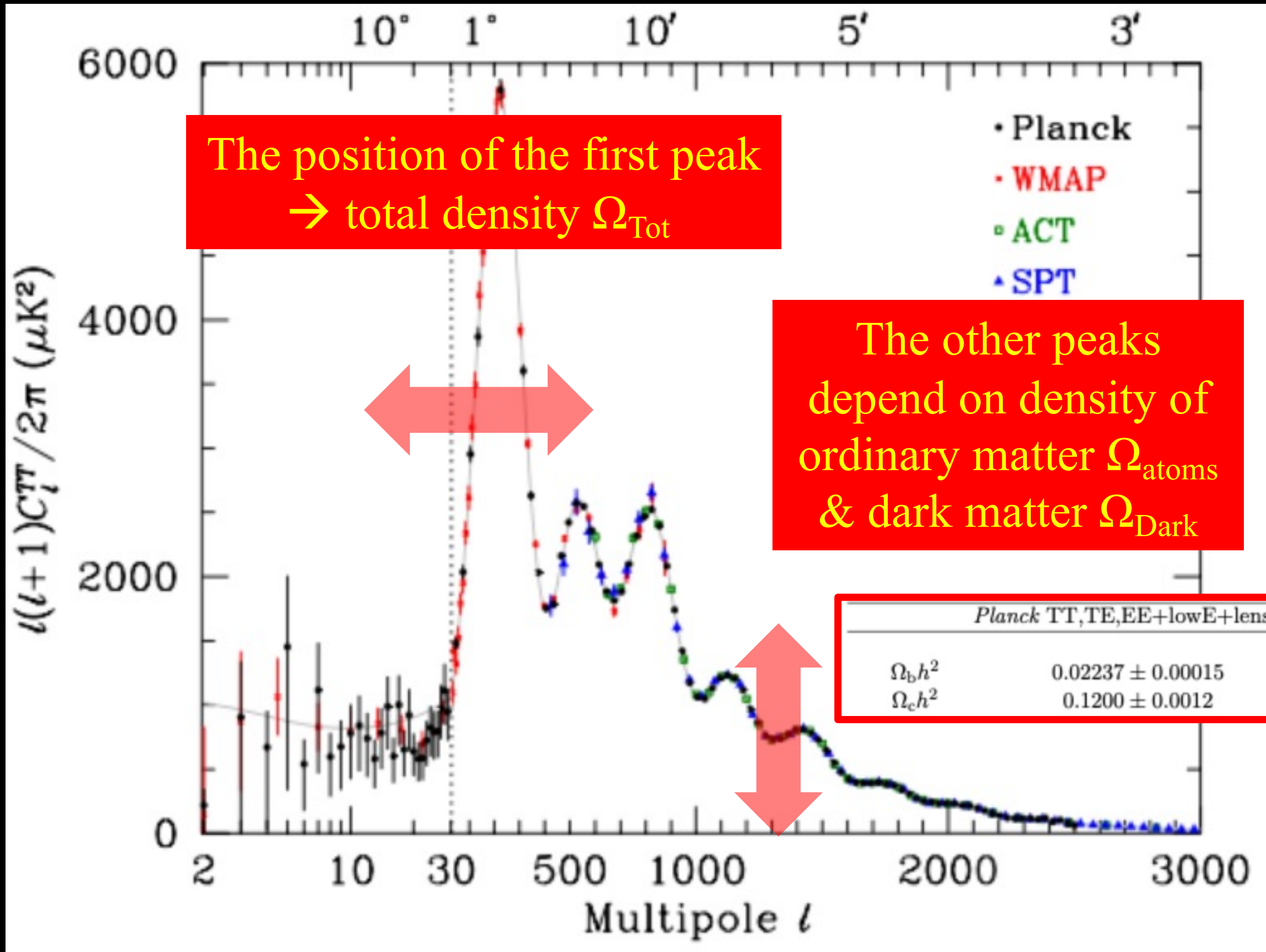
JWST Study of Bullet Cluster



Symbols represent lensed background systems used to map density profile

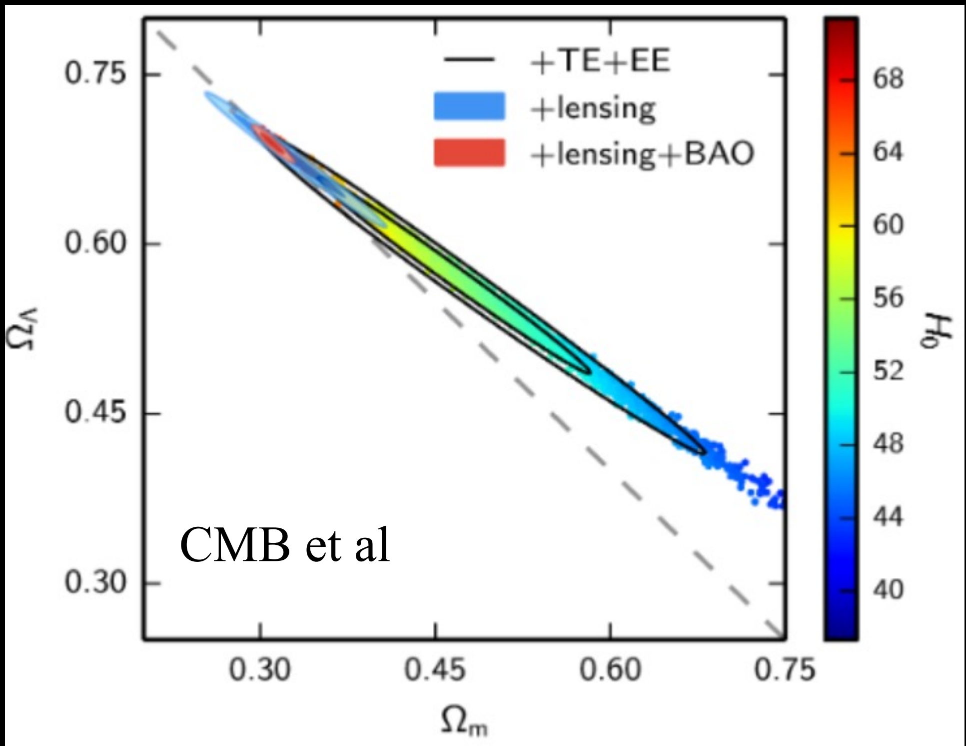
Riharšič et al, arXiv:2601.22245

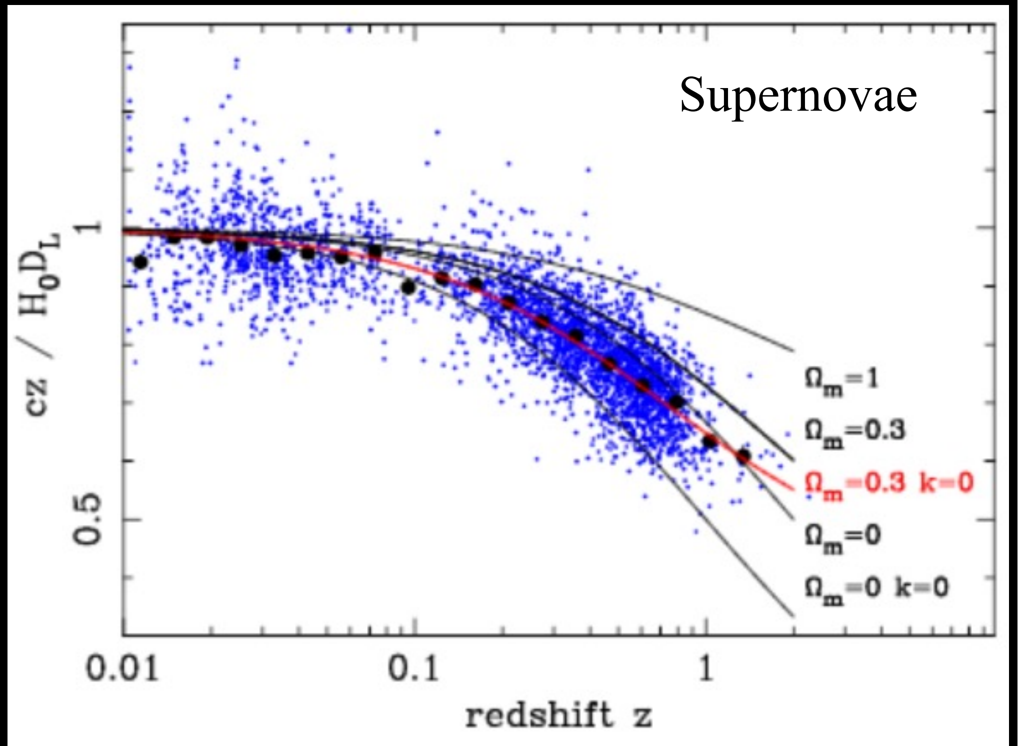
The Spectrum of Fluctuations in the Cosmic Microwave Background (CMB)



	Planck TT,TE,EE+lowE+lensing	P-ACT-LB2
$\Omega_b h^2$	0.02237 ± 0.00015	0.02258 ± 0.00010
$\Omega_c h^2$	0.1200 ± 0.0012	0.1174 ± 0.0006

CMB, BAOs, Lensing and High-z Supernovae





CMB constrains $\Omega_m + \Omega_\Lambda$: Universe almost flat (dashed line)

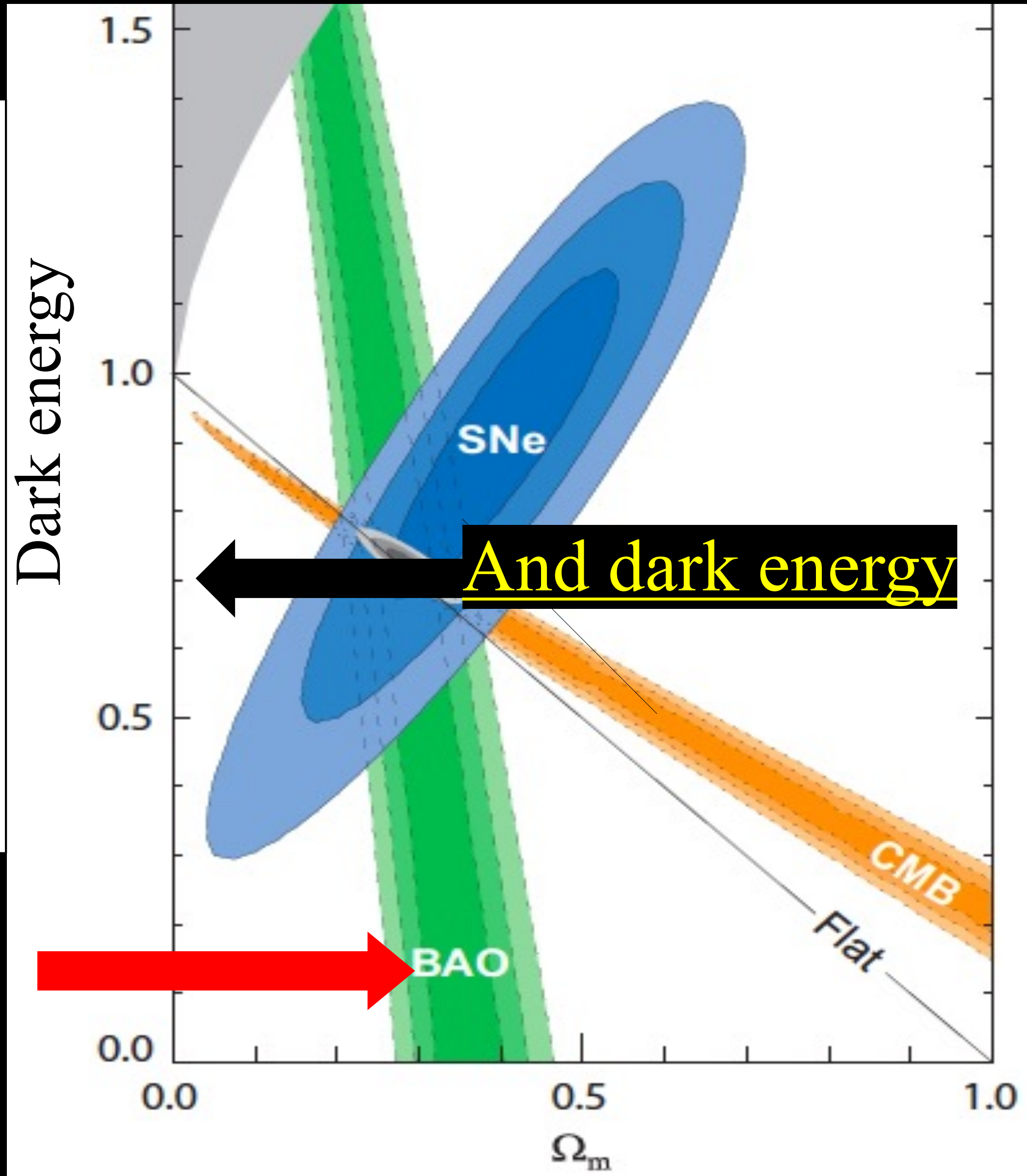
Supernovae constrain $\Omega_m - \Omega_\Lambda$

BAOs constrain Ω_m

Particle Data Group

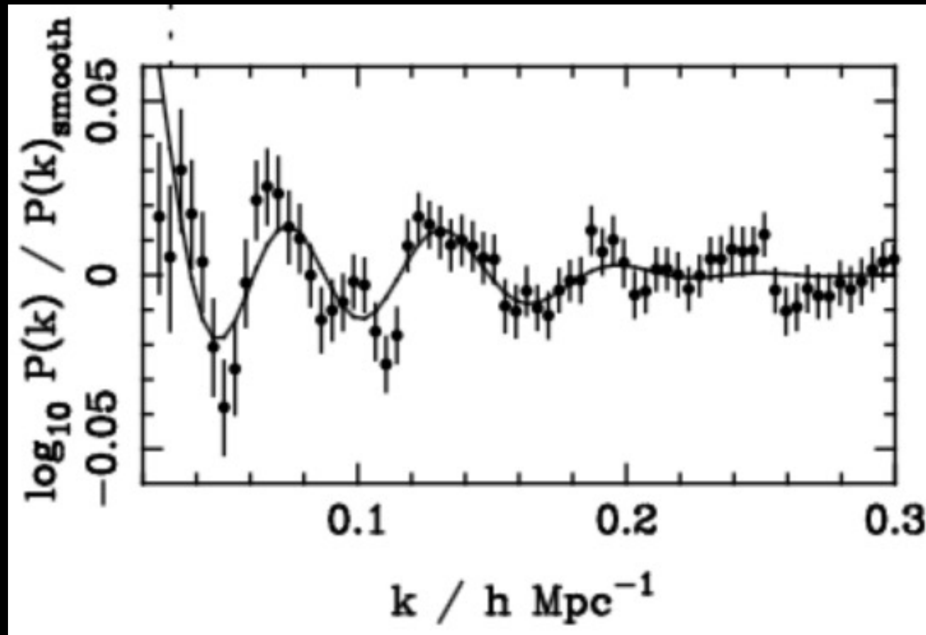
The Content of the Universe

- According to
  - **Microwave background**
  - **Supernovae**
  - **Structures (galaxies, clusters, …) in the Universe**



There is dark matter

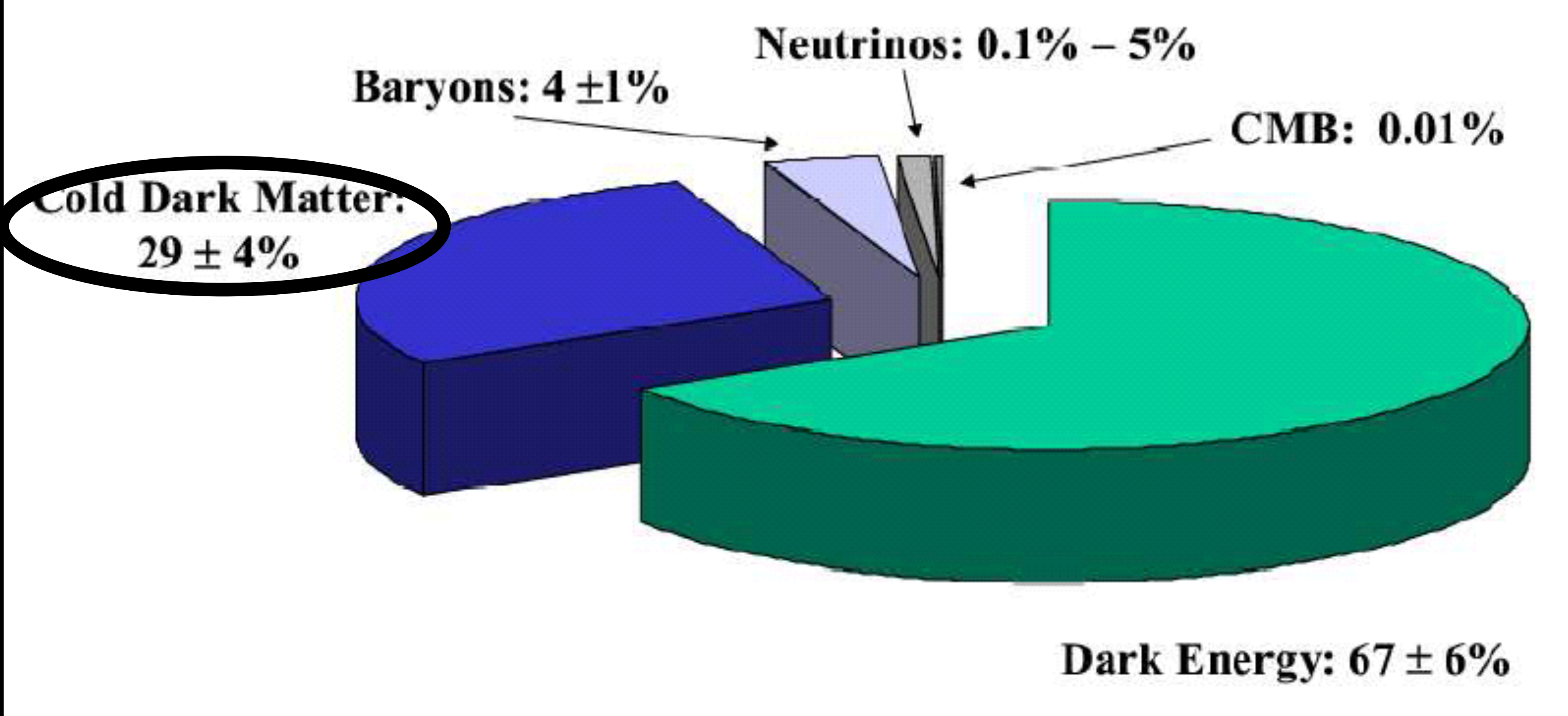
Baryon Acoustic Oscillations



Baryon Acoustic Oscillations (BAOs)
High-density regions generate ripples in large-scale structure

SDSS BOSS survey, Anderson et al, arXiv:1203.6594

Strange Recipe for a Universe

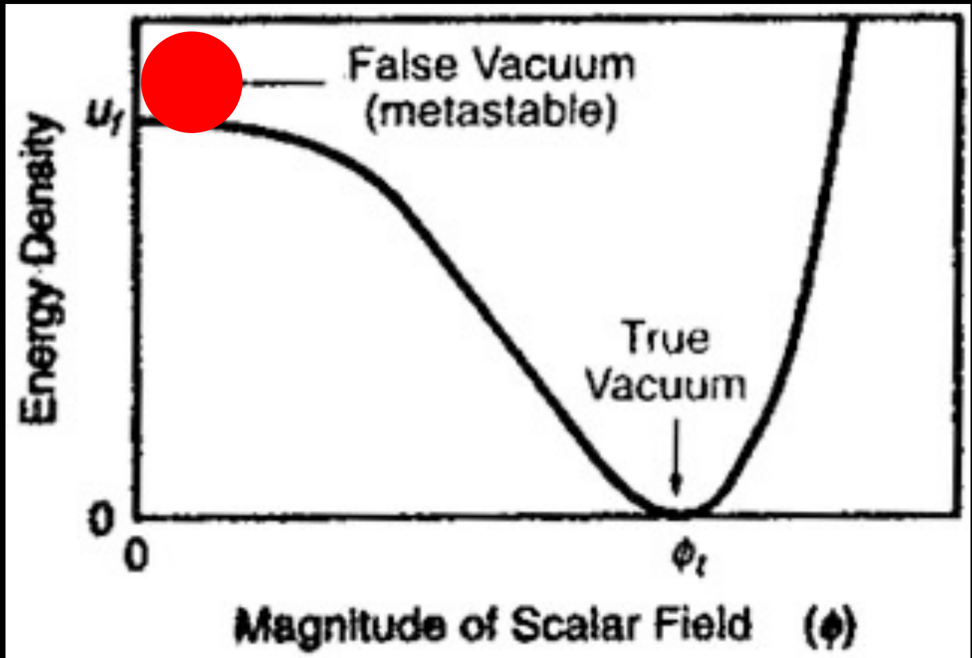


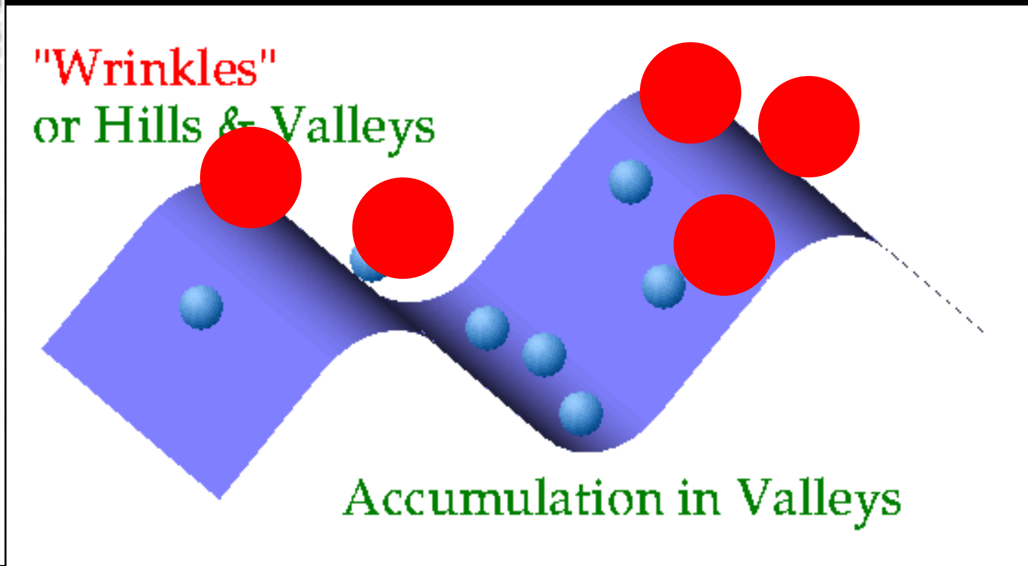
The 'Standard Model' of the Universe indicated by astrophysics and cosmology

The Origin of Structures in the Universe

Small primordial CMB fluctuations: ~ $1/10^5$

Gravitational instability: dark matter falls into the gravitational potential wells, visible matter follows

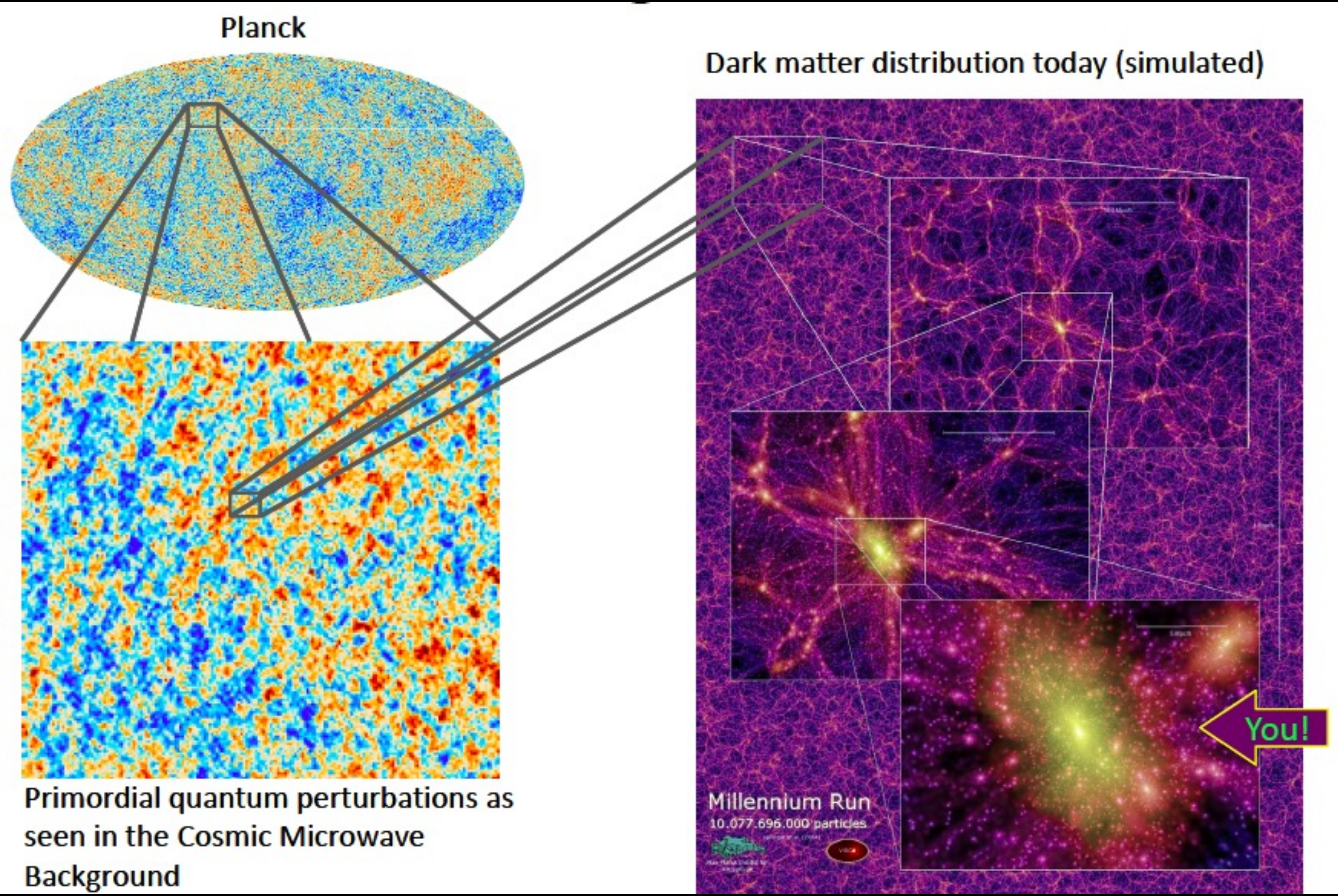




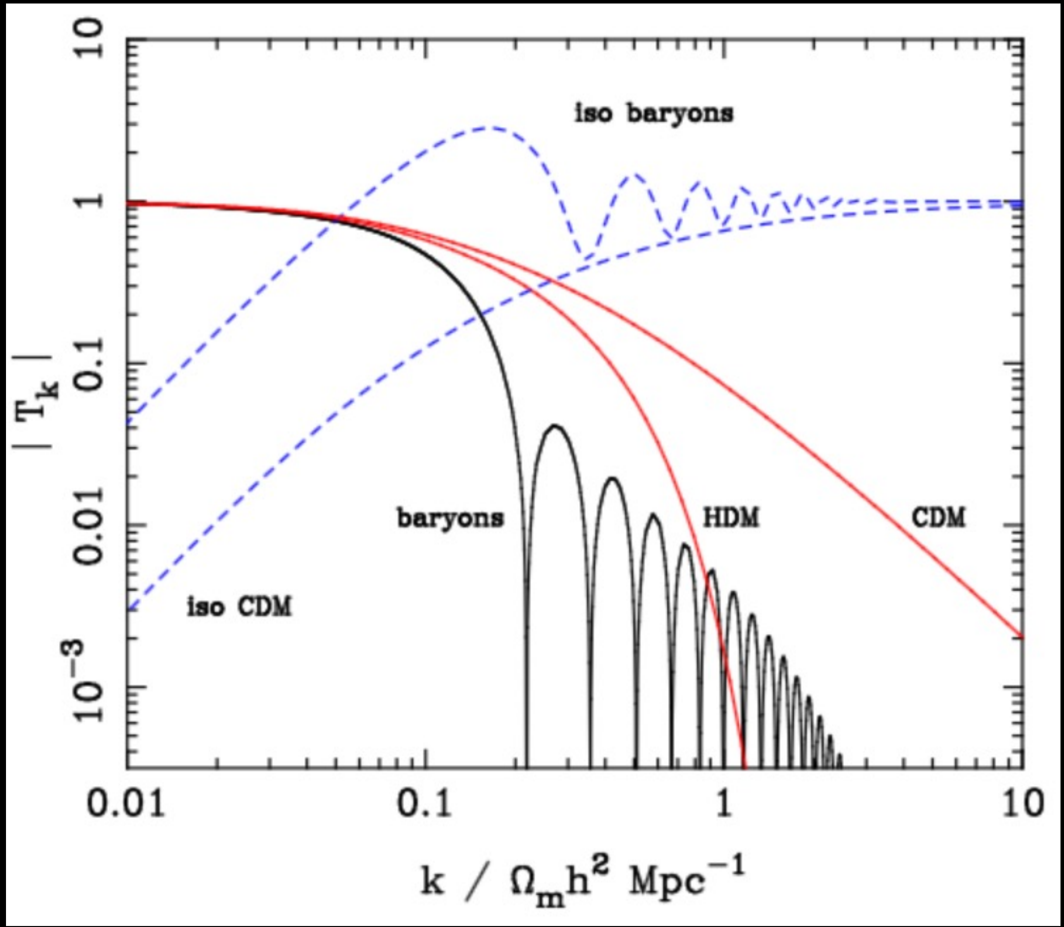
Become density fluctuations

Become structures in Universe

Dark Matter Generated Structures



Spectra of Density Perturbations



Baryon density fluctuations are damped

Cold dark matter density fluctuations persist over large range of scales

Hot dark matter density fluctuations suppressed at small scales (large k)

Particle Data Group

A Successful Theory of the Formation of Structures in the Universe

Dark matter:

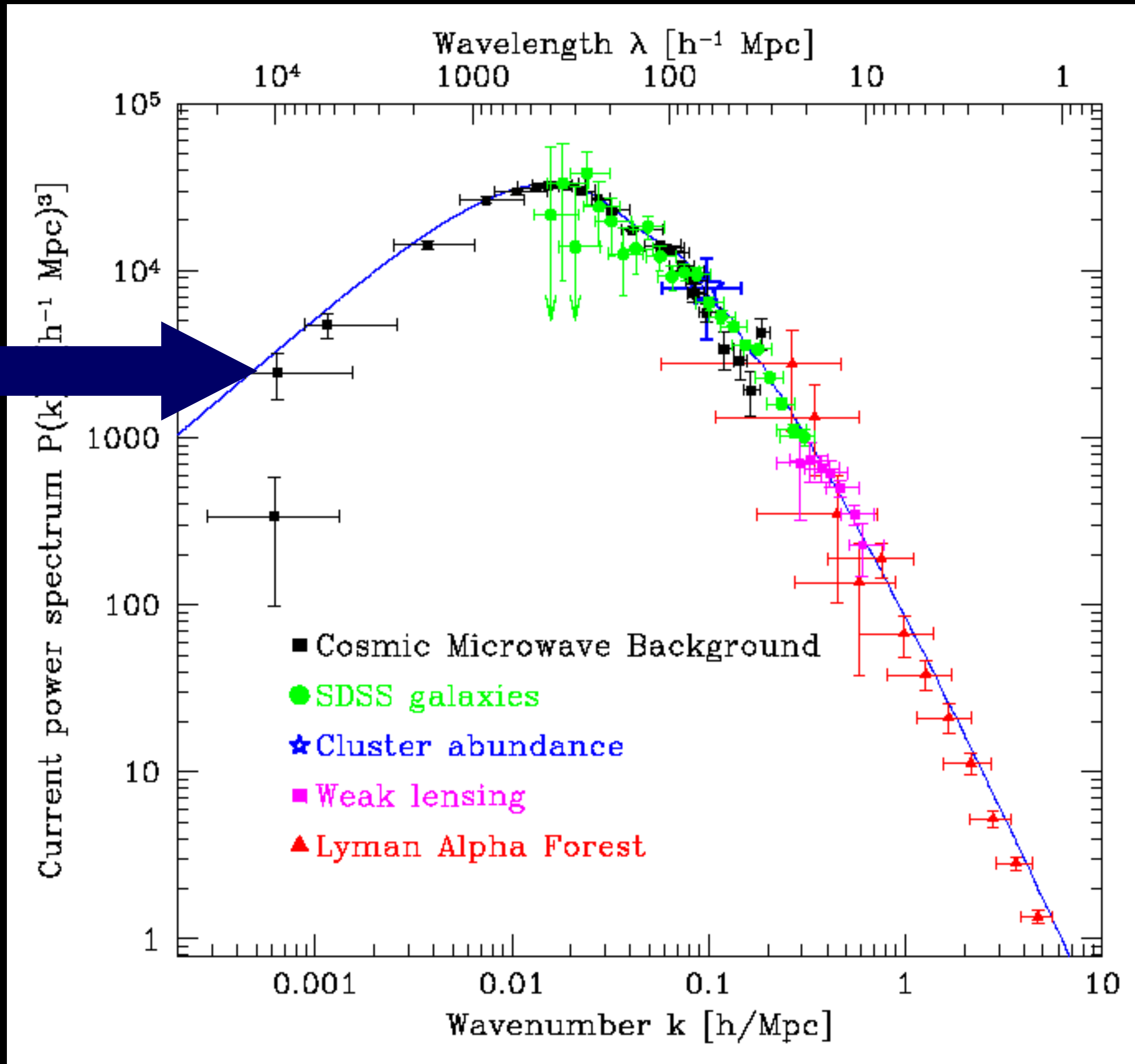
$\Omega_{CDM} \sim 0.25$,

Visible matter:

$\Omega_b \sim 0.05$,

Dark energy:

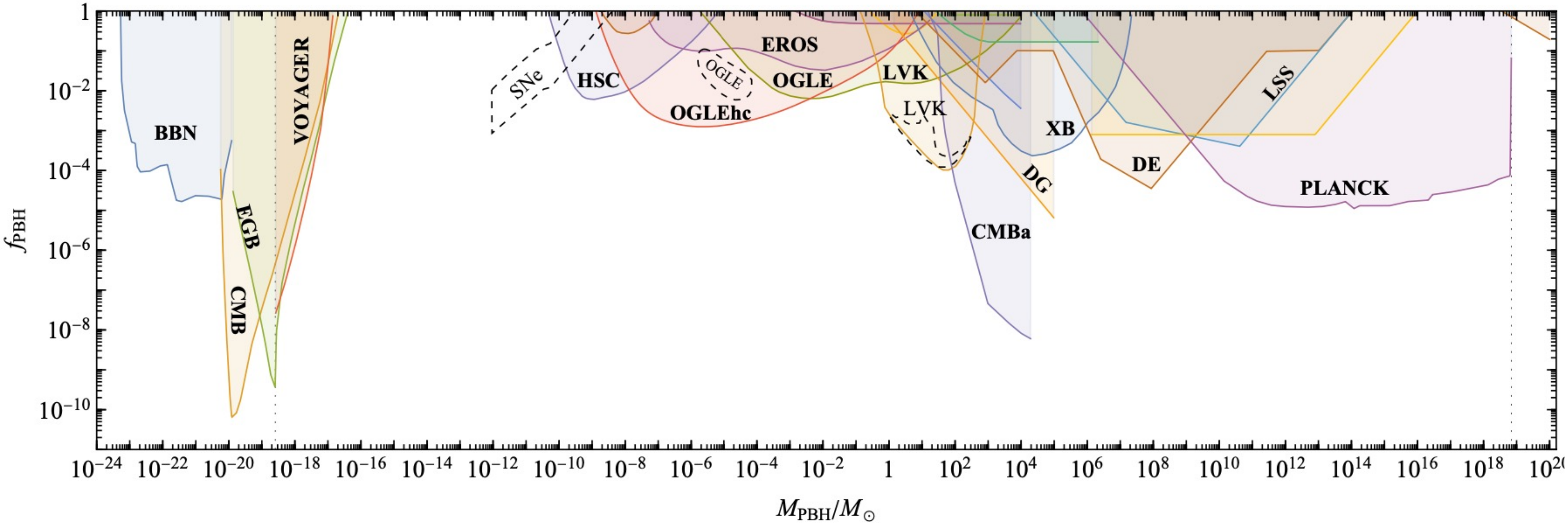
$\Omega_\Lambda \sim 0.7$



Properties of Dark Matter

- Should not have (much) electric charge
  - Otherwise we would have seen it
- Should interact weakly with ordinary matter
  - Otherwise we would have detected it, either directly or astrophysically
- Should not be too light
  - Needed for forming and holding together structures in the Universe: clusters, galaxies, Lyman alpha clouds, … on different scales

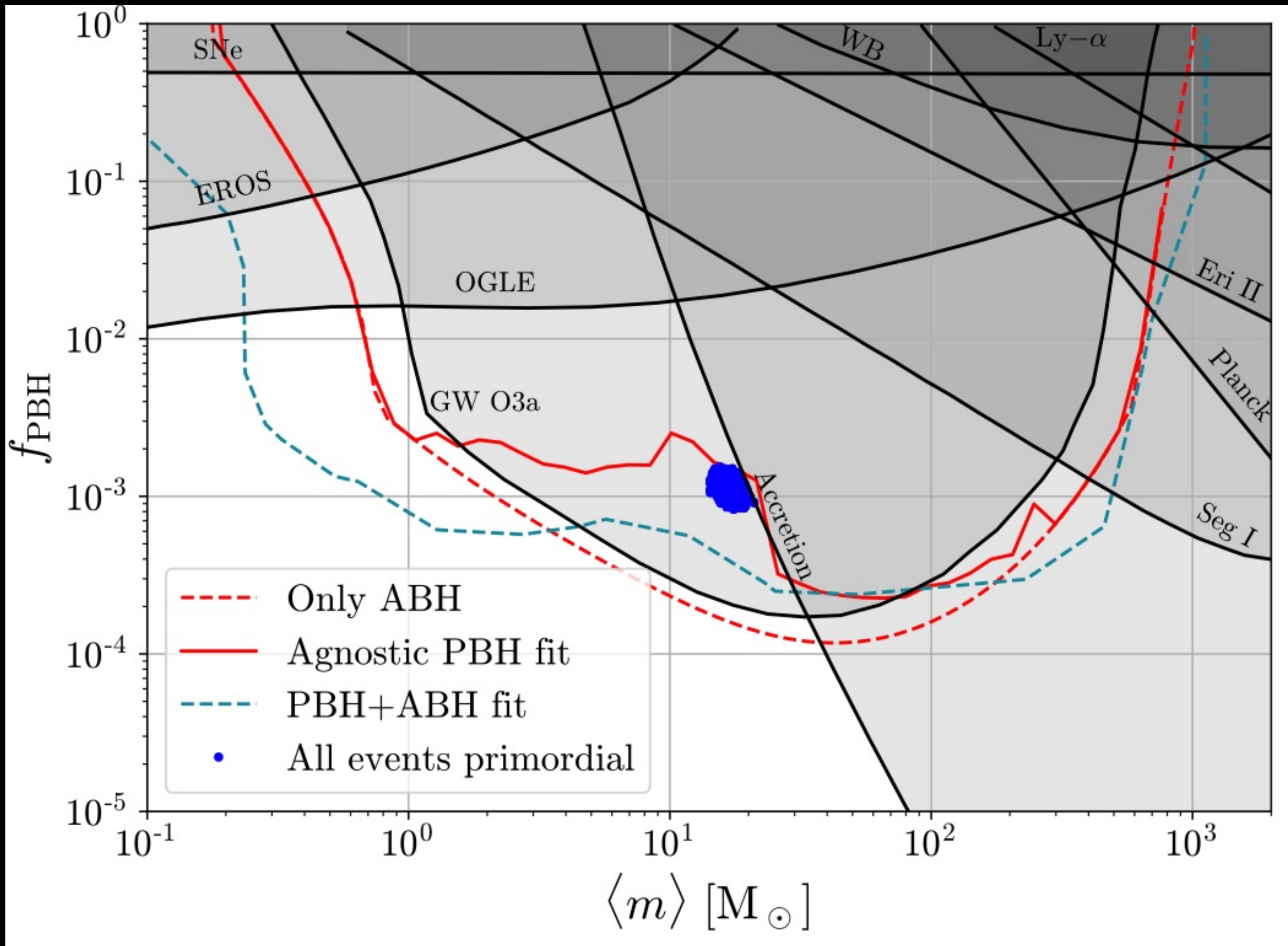
Could Black Holes be the Dark Matter?



- Strong constraints on BHs with masses > solar mass,
in particular masses in the range detected by LIGO/Virgo/Kagra
- BHs could provide all the DM only if masses similar to asteroids
- Would have to be primordial: production mechanism?

Carr et al, arXiv:2601.06024

Constraints on Solar-Mass Black Holes

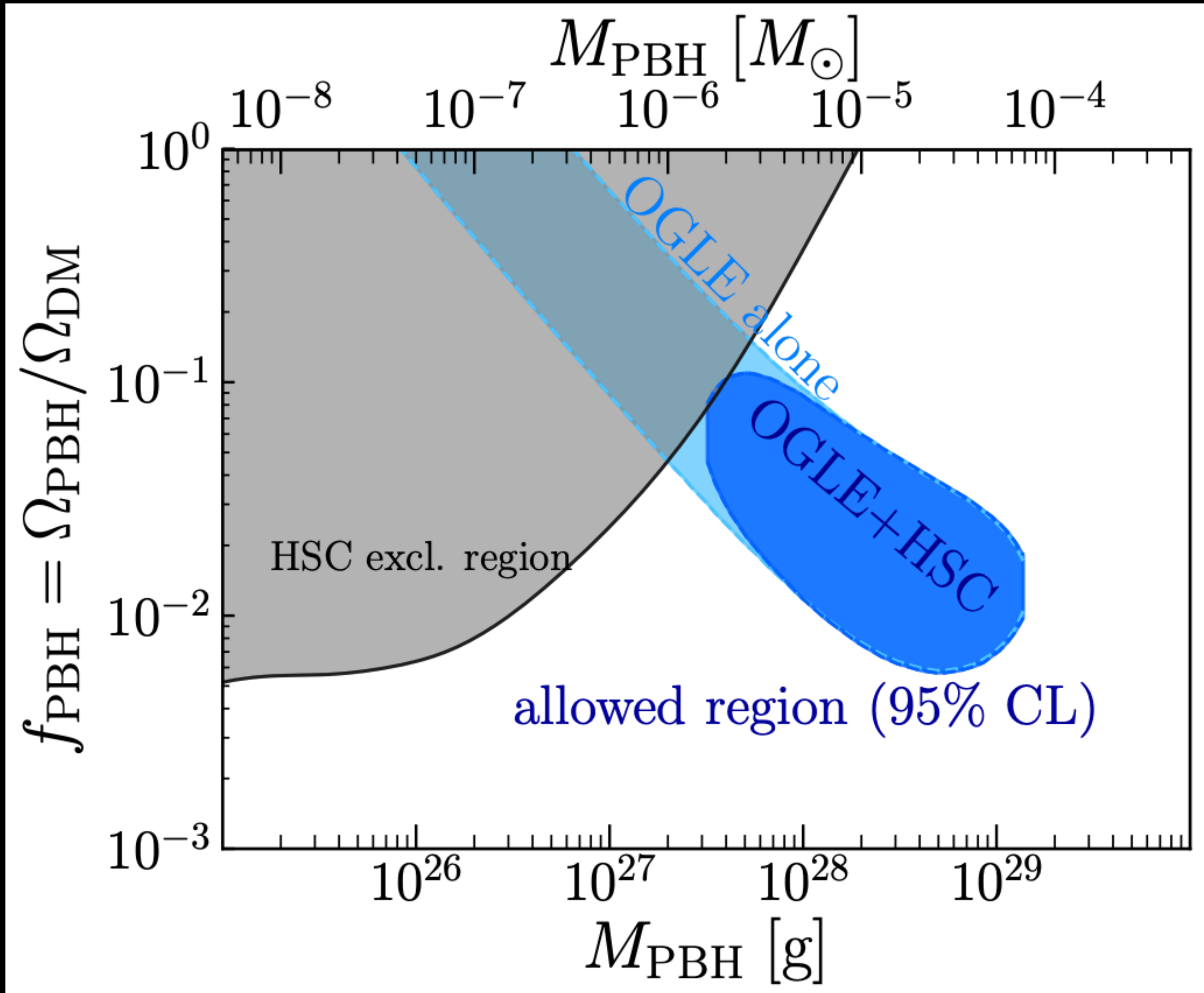


Possible interpretation of LIGO/Virgo/KAGRA events:

Density fraction ~ 10^{-3}

Niikura et al, arXiv:1901.07120

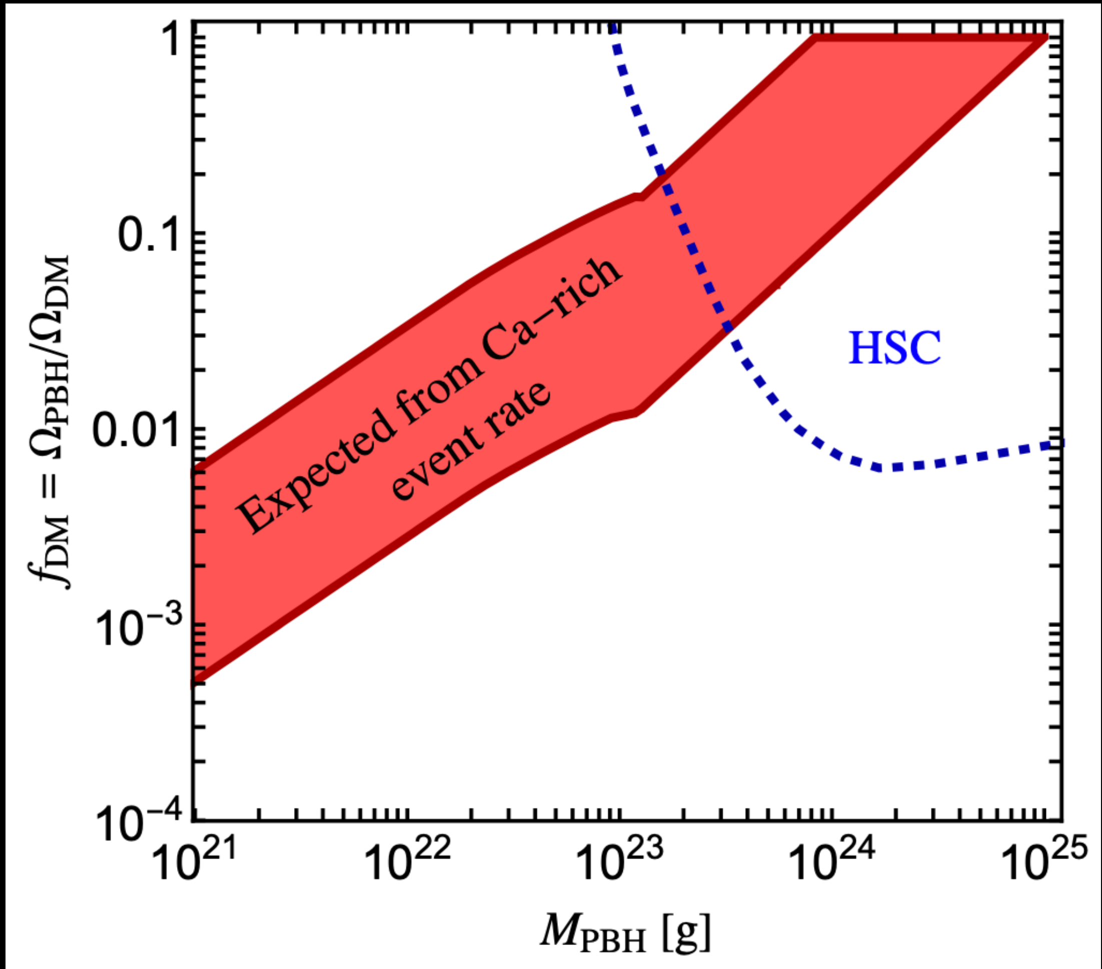
Hint from Microlensing?



Possible interpretation of some microlensing events:
Density fraction ~ 10^{-2}

Carr et al, arXiv:2601.06024

Hint from Unusual Supernovae?

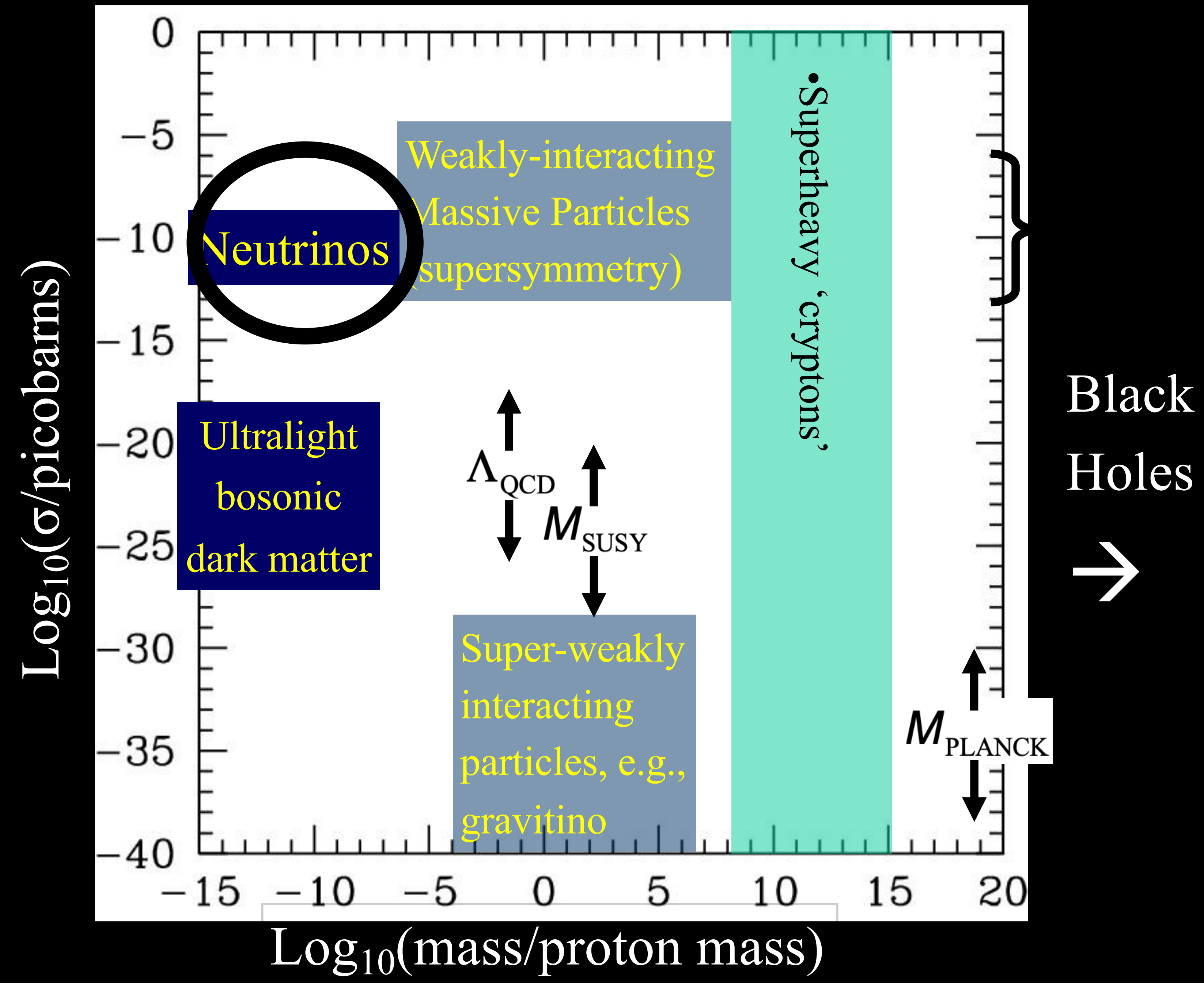


Triggered by white dwarf – BH collisions?

Density fraction ~ 10^{-2}

Smirnov, Goobar, Linden & Mörtsell, arXiv:2211.00013

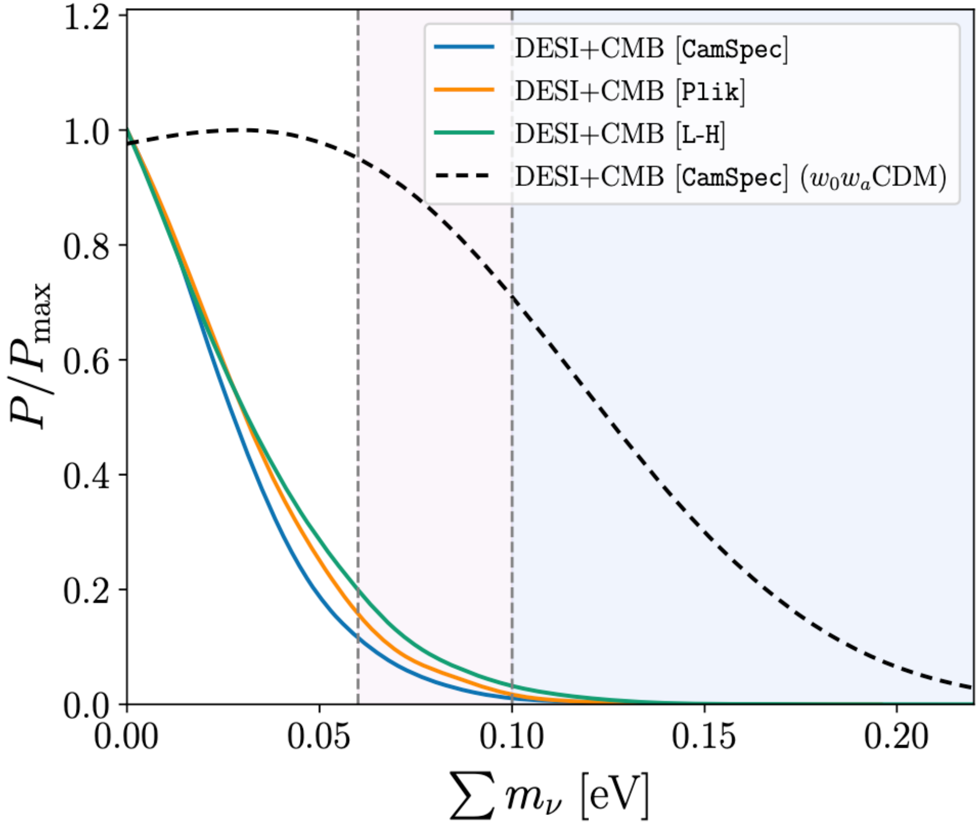
Particle Dark Matter Candidates

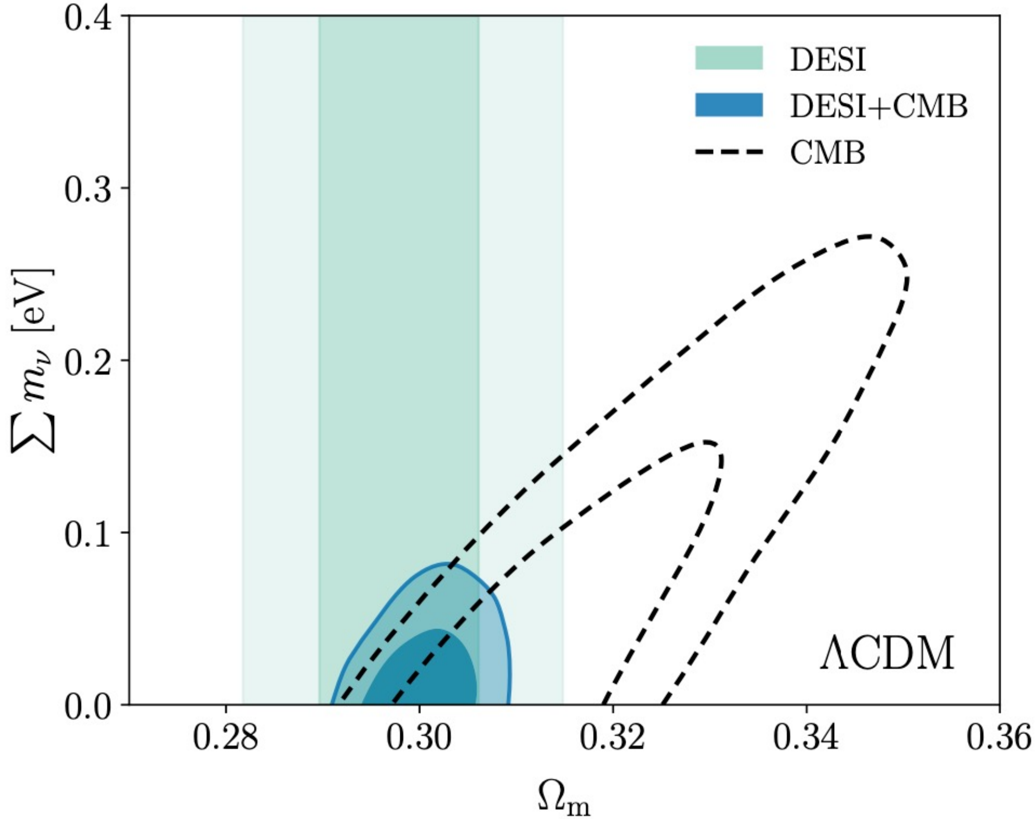


Neutrinos

- They exist! ☺️
- They have weak interactions ☺️
- They have masses ☺️
  - As indicated by neutrino oscillations
- But their masses are very small ☹️
  - < 1 eV (= 1/1000,000,000 of proton mass)
- Not able to grow all structures in Universe ☹️
  - (run away from small structures)
- Maybe some other neutrinos beyond the Standard Model? **Sterile neutrinos?**

Constraints on Matter Density, Neutrino Masses from Large-Scale Structure





$\Sigma\, m_\nu < 0.064$

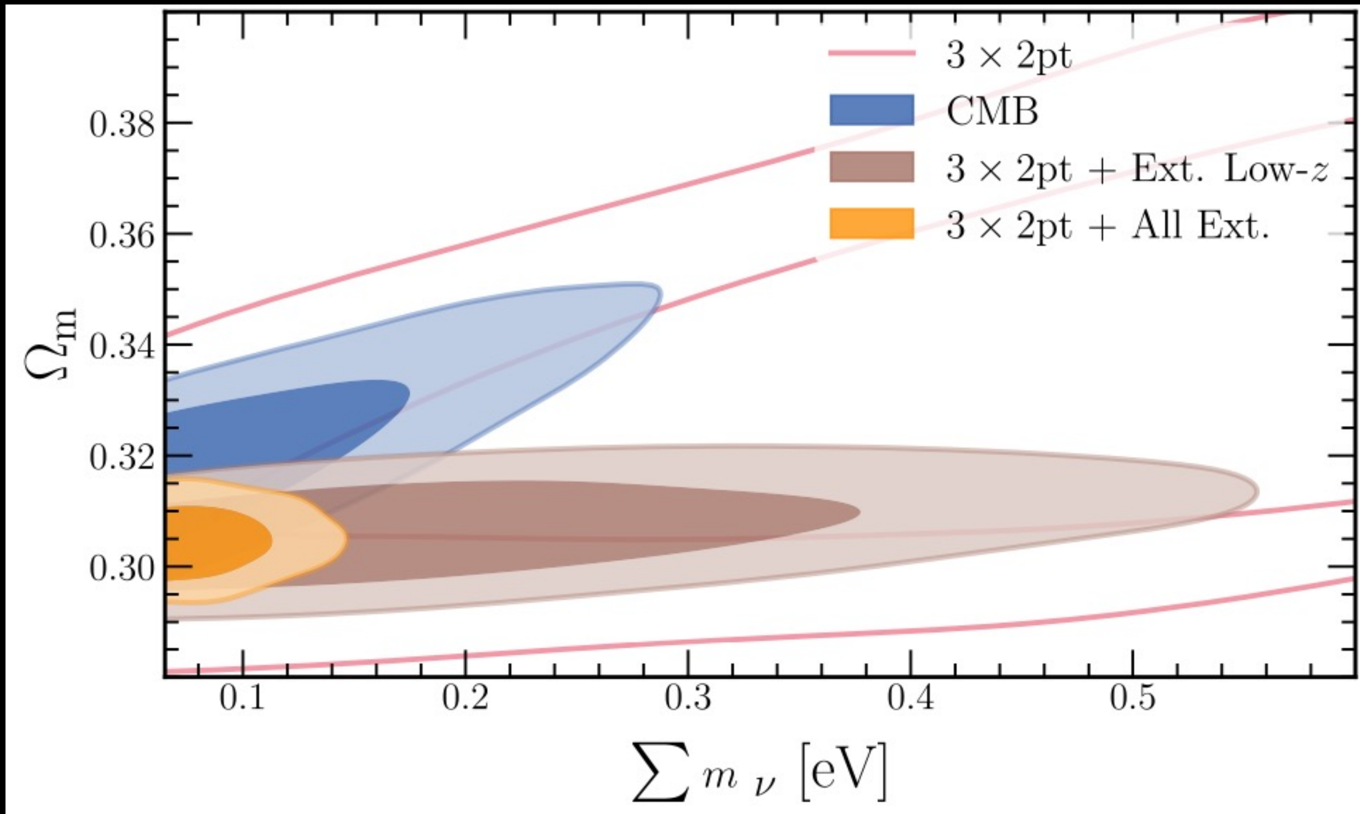
but analysis does not exclude negative values

$\Omega_m \approx 0.301 \pm 0.004$

independent of neutrino masses

DESI Collaboration, arXiv:2503.14738

Constraint on Sum of Neutrino Masses
from Large-Scale Structure



$\Sigma\, m_\nu < 0.14$ eV (95%)

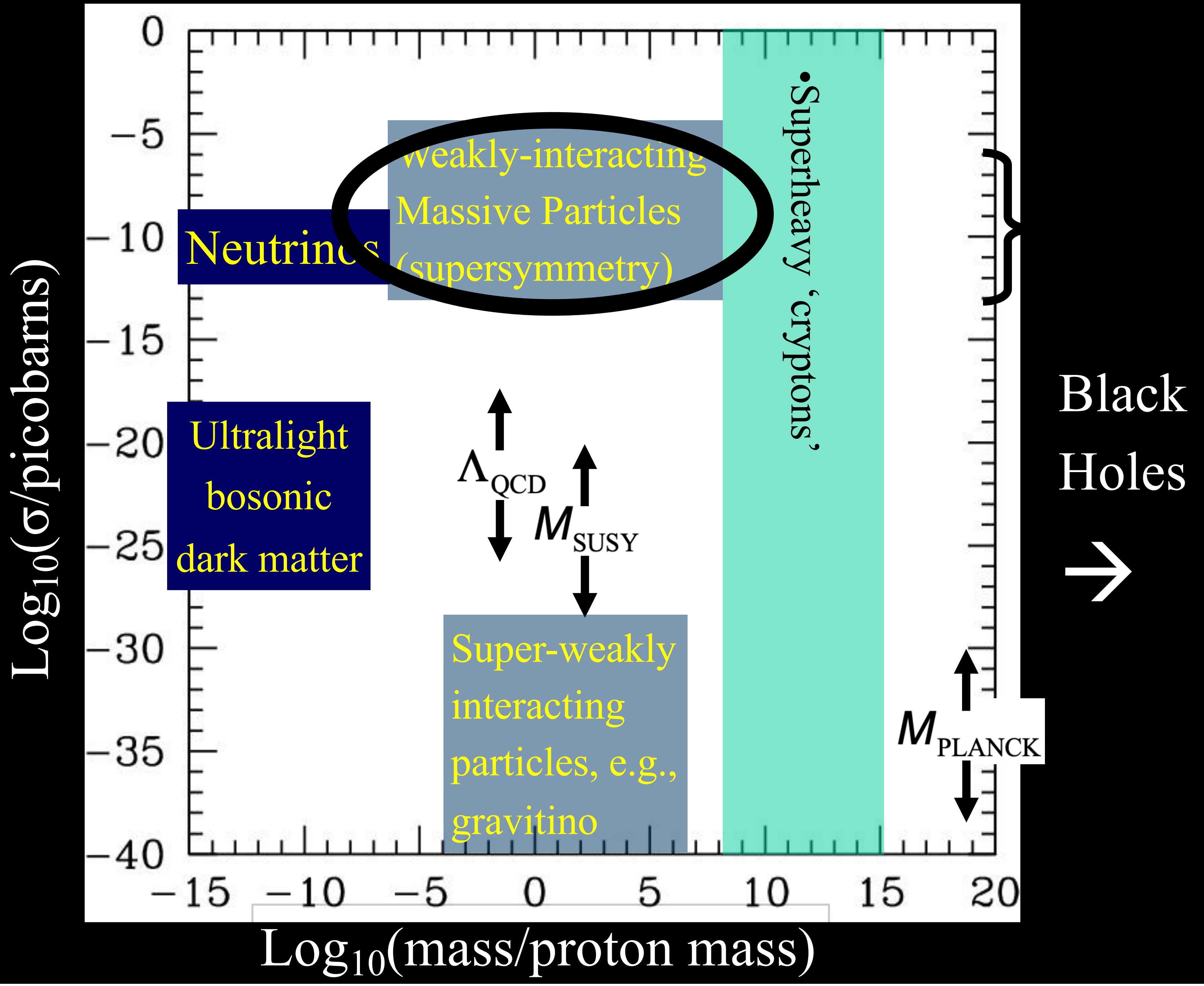
analysis assumes sum is positive

$\Omega_m \approx 0.302 \pm 0.003$

from combined analysis

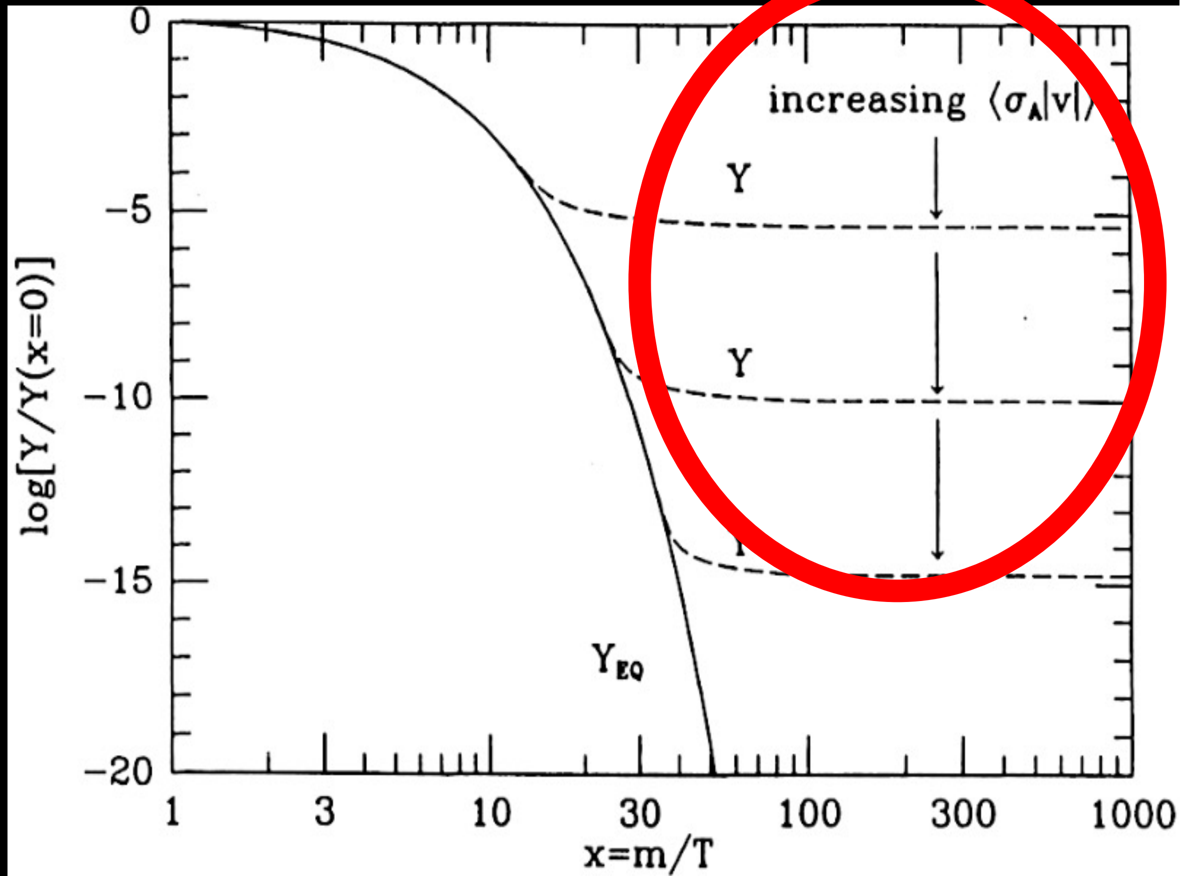
DES Collaboration, arXiv:2601.14559

Particle Dark Matter Candidates

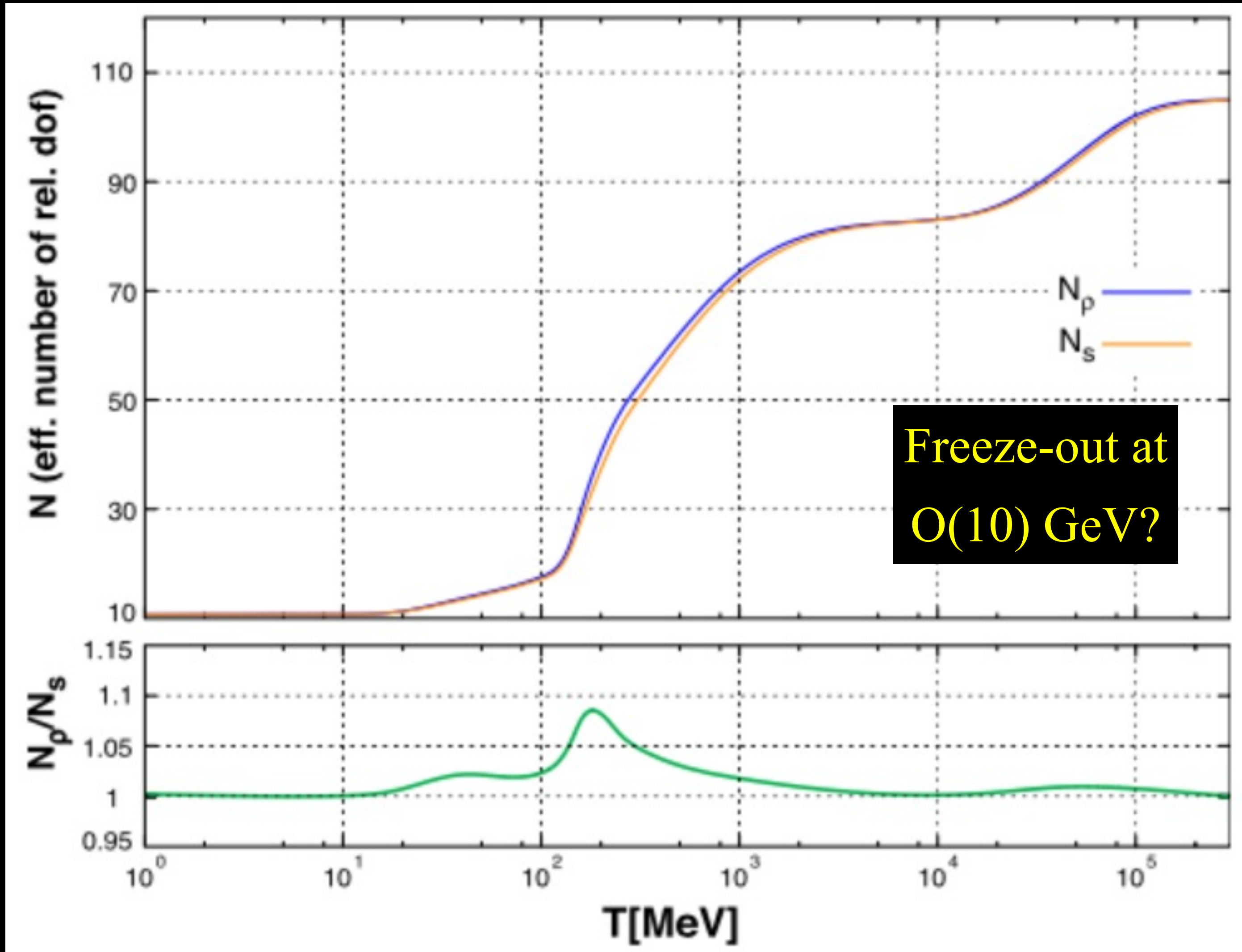


Weakly-Interacting Massive Particles (WIMPs)

- Expected to have been numerous in the primordial Universe when it was a fraction of a second old, full of a primordial hot soup
- Would have cooled down as Universe expanded
- Interactions would have weakened
- WIMPs decoupled from visible matter, Annihilations stopped
- "Freeze-out"
- Larger σ → lower Y



‘Standard’ Thermal History of Early Universe



Comparison between energy density and entropy through QCD pase transition, quark thresholds

The WIMP ‘Miracle’

- The TeV scale from cosmology: $\mathrm{TeV} \simeq \sqrt{M_{\mathrm{Pl}} \times 2.7\,\mathrm{K}}$
- Generic density from freeze-out:

$$\Omega_X h_0^2 \simeq \frac{1}{10^3 \langle \sigma v \rangle} \frac{1}{M_{\mathrm{Pl}} \times 2.7\,\mathrm{K}} \simeq \frac{1}{10^3 \langle \sigma v \rangle} \frac{1}{\mathrm{TeV}^2}$$

- Generic annihilation cross-section: $\sigma v \simeq \frac{c\alpha^2}{m^2}$

$$m \simeq \sqrt{M_{\mathrm{Pl}} \times 2.7\,\mathrm{K}}\; 16\alpha\sqrt{C}\sqrt{\frac{\Omega_X h_0^2}{0.25}}$$

- Generic relic mass:

$$\simeq \mathrm{TeV}\; 16\alpha\sqrt{C}\sqrt{\frac{\Omega_X h_0^2}{0.25}}\,.$$

- Putting the numbers in:

$$m \lesssim \tfrac{1}{2}\sqrt{10C}\,\mathrm{TeV} \lesssim 5\,\mathrm{TeV}$$

WIMP Candidates

- Could have right density if weigh 100 to 1000 GeV (accessible to LHC experiments?)
- Present in many extensions of Standard Model
- Particularly in attempts to understand strength of weak interactions, mass of Higgs boson
- Examples:
  - Extra dimensions of space
  - **Supersymmetry**

What lies beyond the Standard Model?

Supersymmetry?

New motivations
From LHC Run 1

- Stabilize electroweak vacuum
- Successful prediction for Higgs mass
  - Should be < 130 GeV in simple models
- Successful predictions for couplings
  - Should be within few % of SM values
- Naturalness, GUTs, string, …, **dark matter**

Loop Corrections to Higgs Mass^2

- Consider generic fermion and boson loops:

- Each is quadratically divergent: $\int^{\Lambda} d^4k/k^2$

$$\Delta m_H^2 = -\frac{y_f{}^2}{16\pi^2}[2\Lambda^2 + 6m_f^2 \ln(\Lambda/m_f) + \ldots]$$

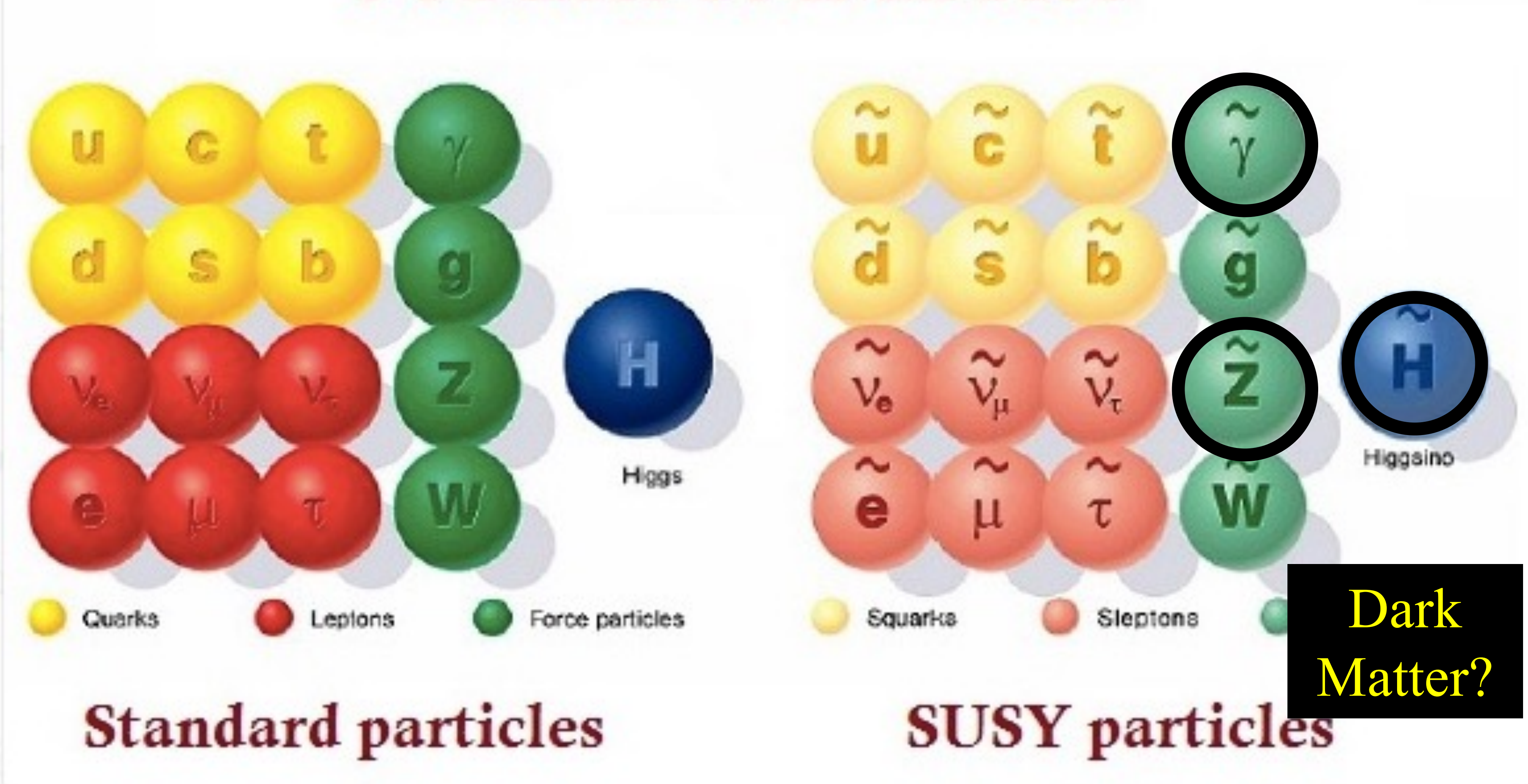
$$\Delta m_H^2 = \frac{\lambda_S}{16\pi^2}[\Lambda^2 - 2m_S^2 \ln(\Lambda/m_S) + \ldots]$$

- Leading divergence cancelled if

$$\lambda_S = y_f^2 \text{ x } 2$$

Supersymmetry!

Minimal Supersymmetric Extension of the Standard Model



Minimal Supersymmetric Extension of the Standard Model (MSSM)

- Double up the known particles:

$$\begin{pmatrix} \frac{1}{2} \\ 0 \end{pmatrix} \; e.g., \; \begin{pmatrix} \ell\;(lepton) \\ \tilde{\ell}\;(slepton) \end{pmatrix} \; or \; \begin{pmatrix} q\;(quark) \\ \tilde{q}\;(squark) \end{pmatrix}$$

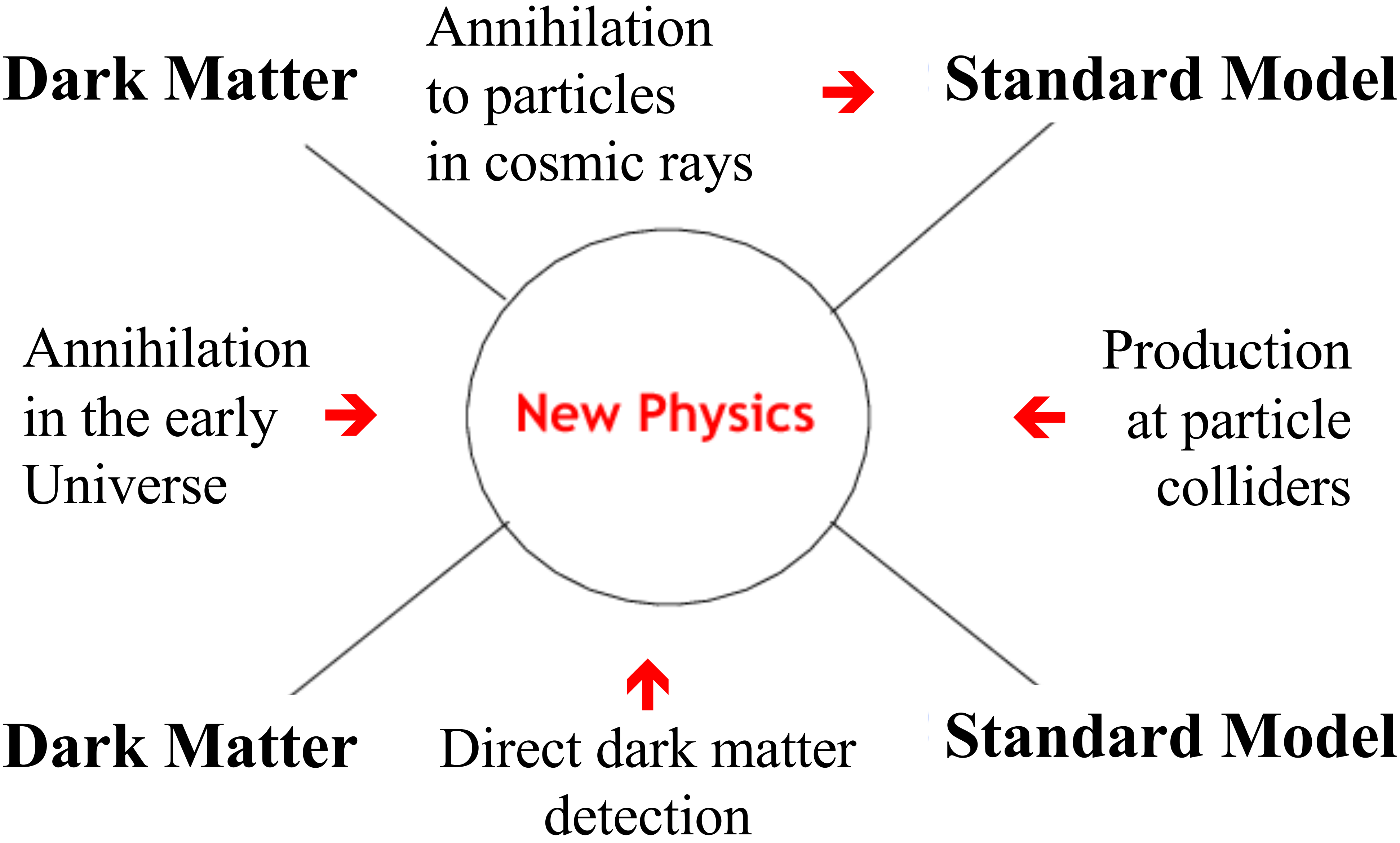
$$\begin{pmatrix} 1 \\ \frac{1}{2} \end{pmatrix} \; e.g., \; \begin{pmatrix} \gamma\;(photon) \\ \tilde{\gamma}\;(photino) \end{pmatrix} \; or \; \begin{pmatrix} g\;(gluon) \\ \tilde{g}\;(gluino) \end{pmatrix}$$

- Two Higgs doublets
  - 5 physical Higgs bosons:
  - 3 neutral, 2 charged
- Lightest neutral supersymmetric Higgs looks like the single Higgs in the Standard Model

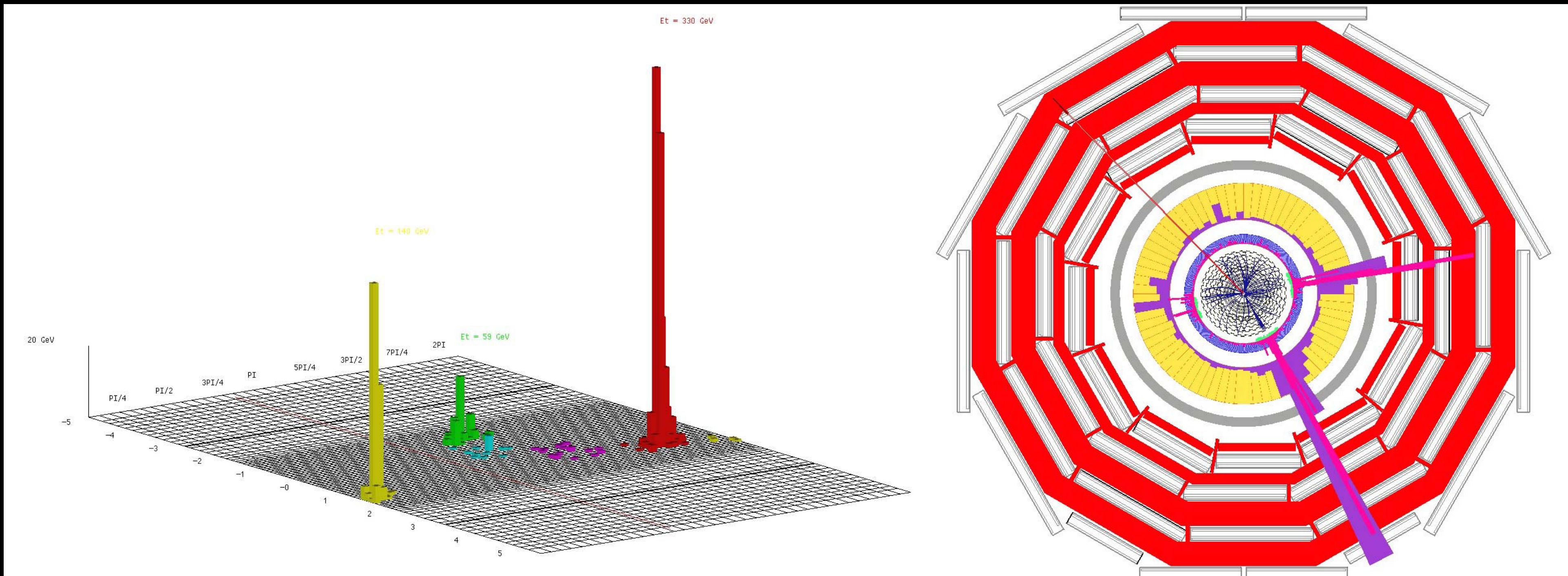
Lightest Sparticle as Dark Matter?

- No strong or electromagnetic interactions
  - **Otherwise would bind to matter**
  - **Detectable as anomalous heavy nucleus**
- Possible weakly-interacting scandidates
  - **Sneutrino**
    - (Excluded by LEP, direct searches)
  - **Lightest neutralino χ** (partner of Z, H, γ)
  - **Gravitino**
    - (nightmare for direct detection)

Searches for WIMP Dark Matter

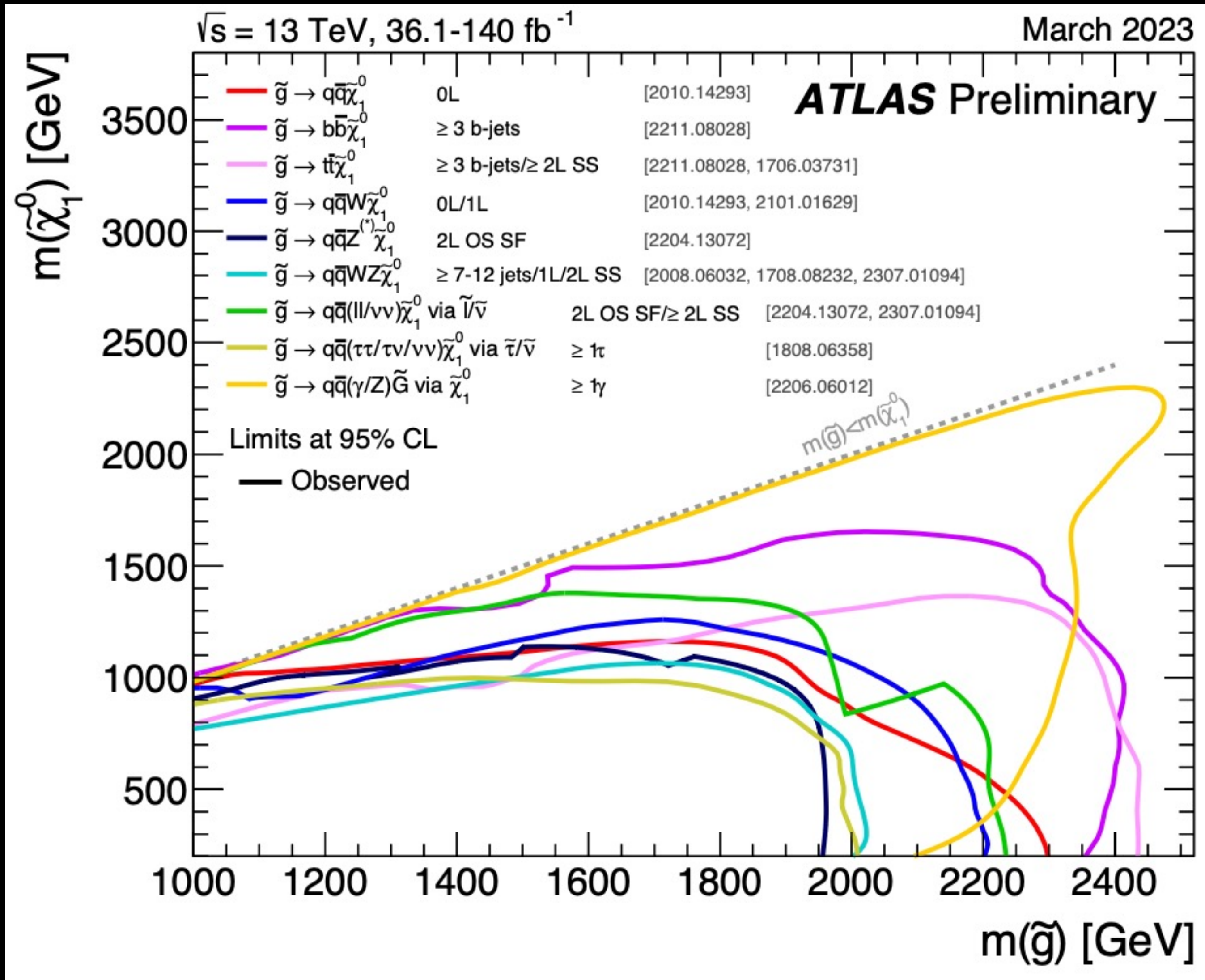


Classic DM Signature at Collider



Missing transverse energy
carried away by dark matter particles

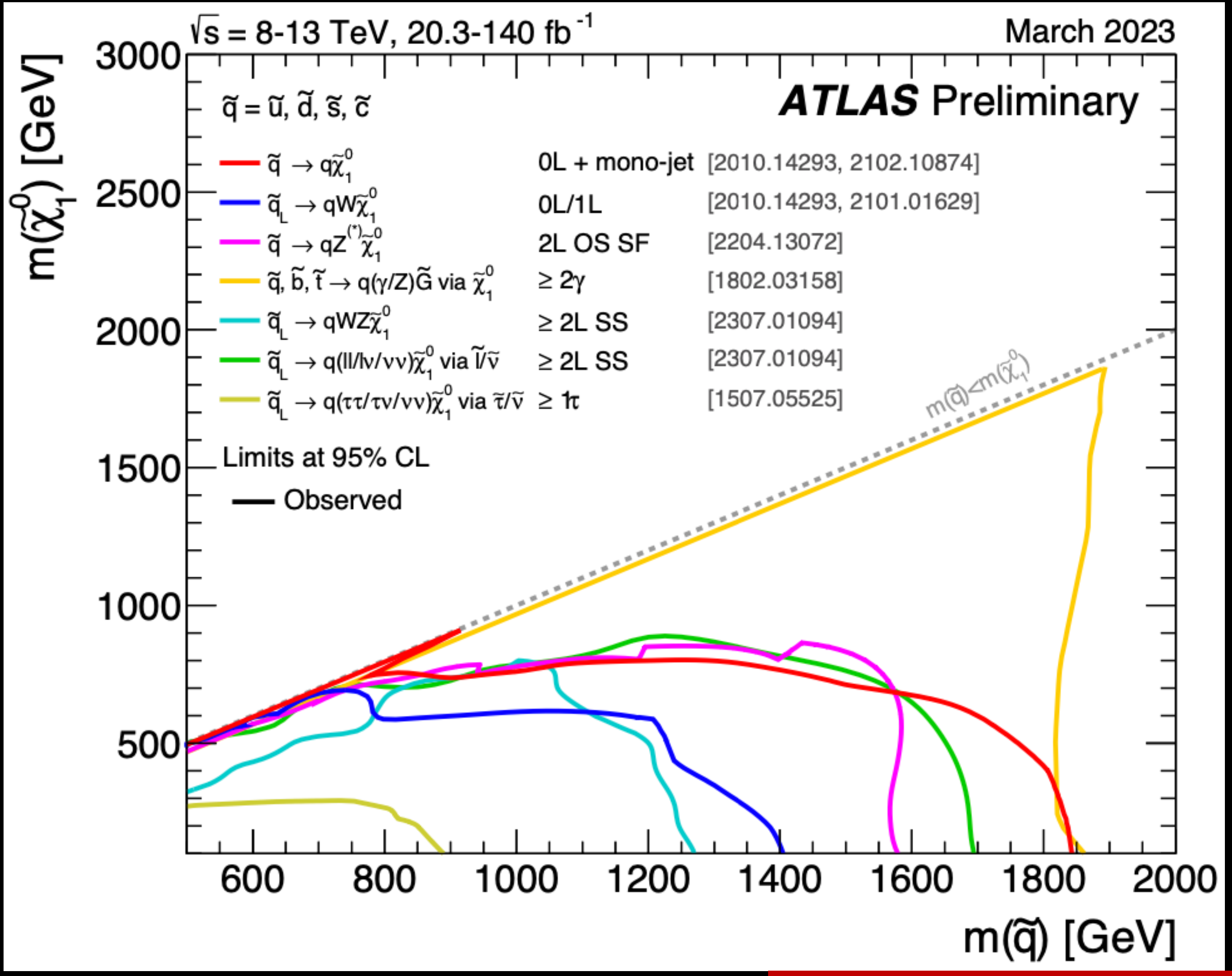
LHC Searches for Gluinos



Beware: Quoted limits often assume specific decays (not general) or mass relations (e.g., CMSSM)

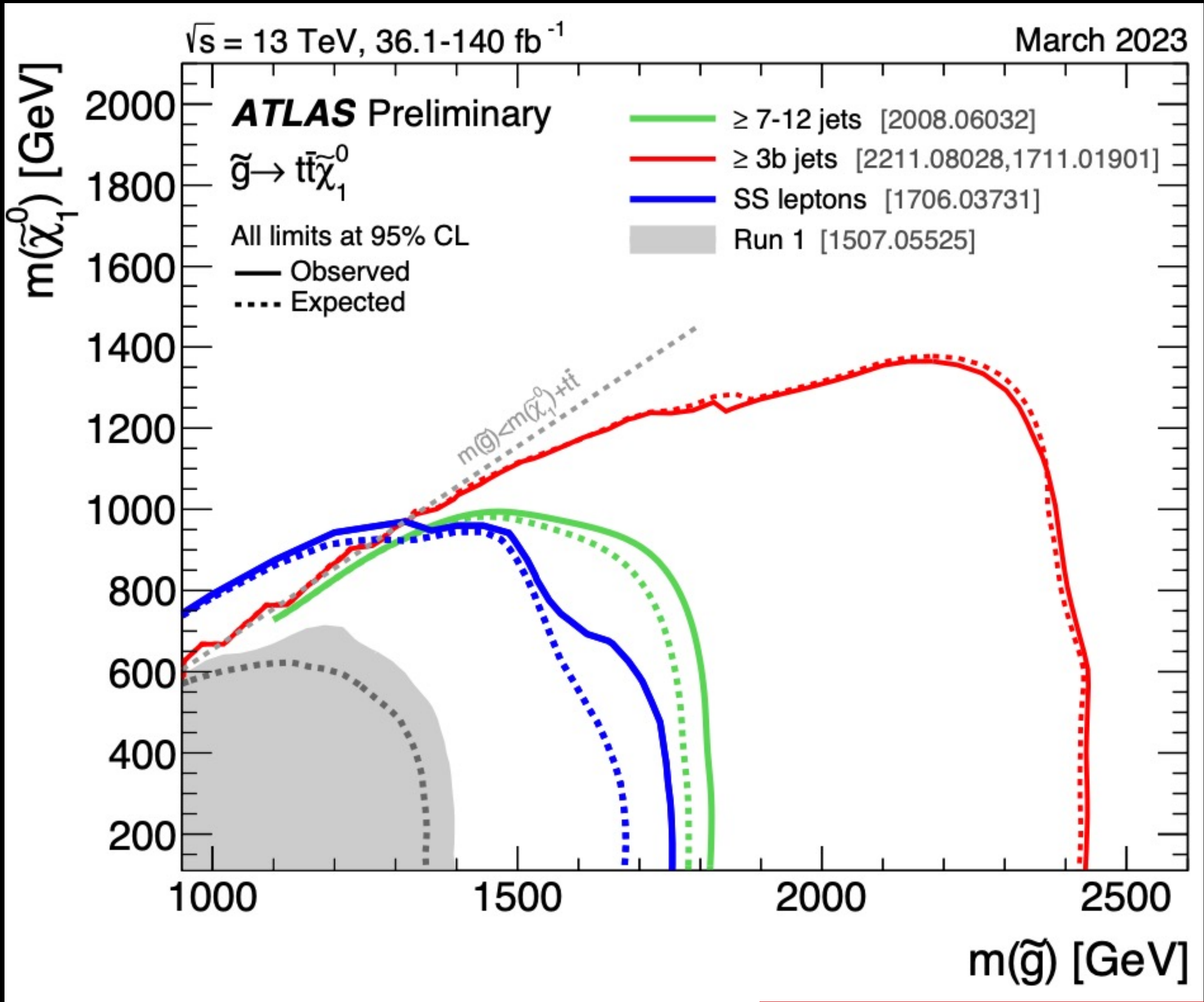
ATLAS Collaboration, ATL-PHYS-PUB-014

LHC Searches for Squarks



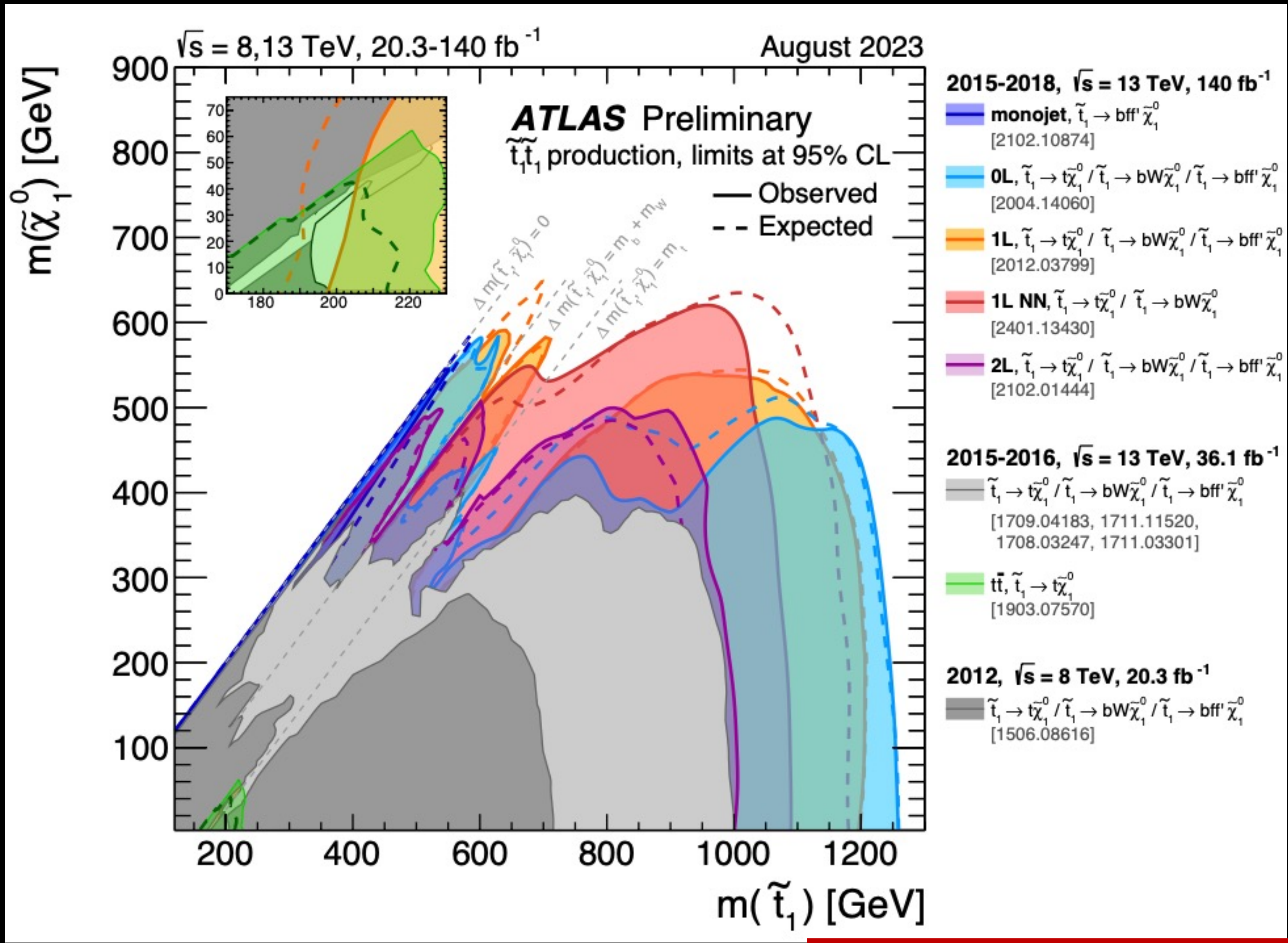
ATLAS Collaboration, ATL-PHYS-PUB-014

Searches for Gluino Decays to Tops



ATLAS Collaboration, ATL-PHYS-PUB-014

Searches for Light Stop Squarks



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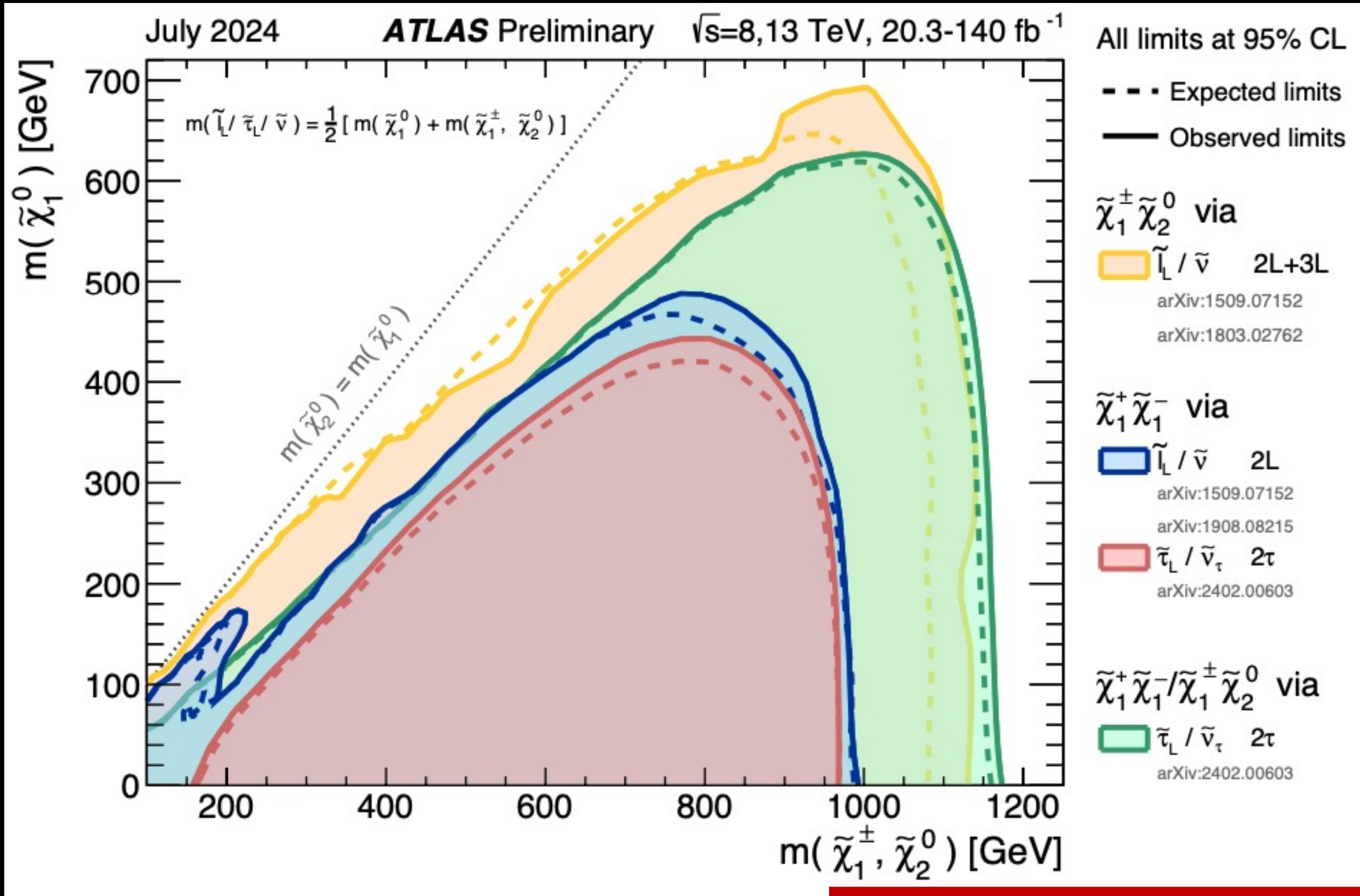
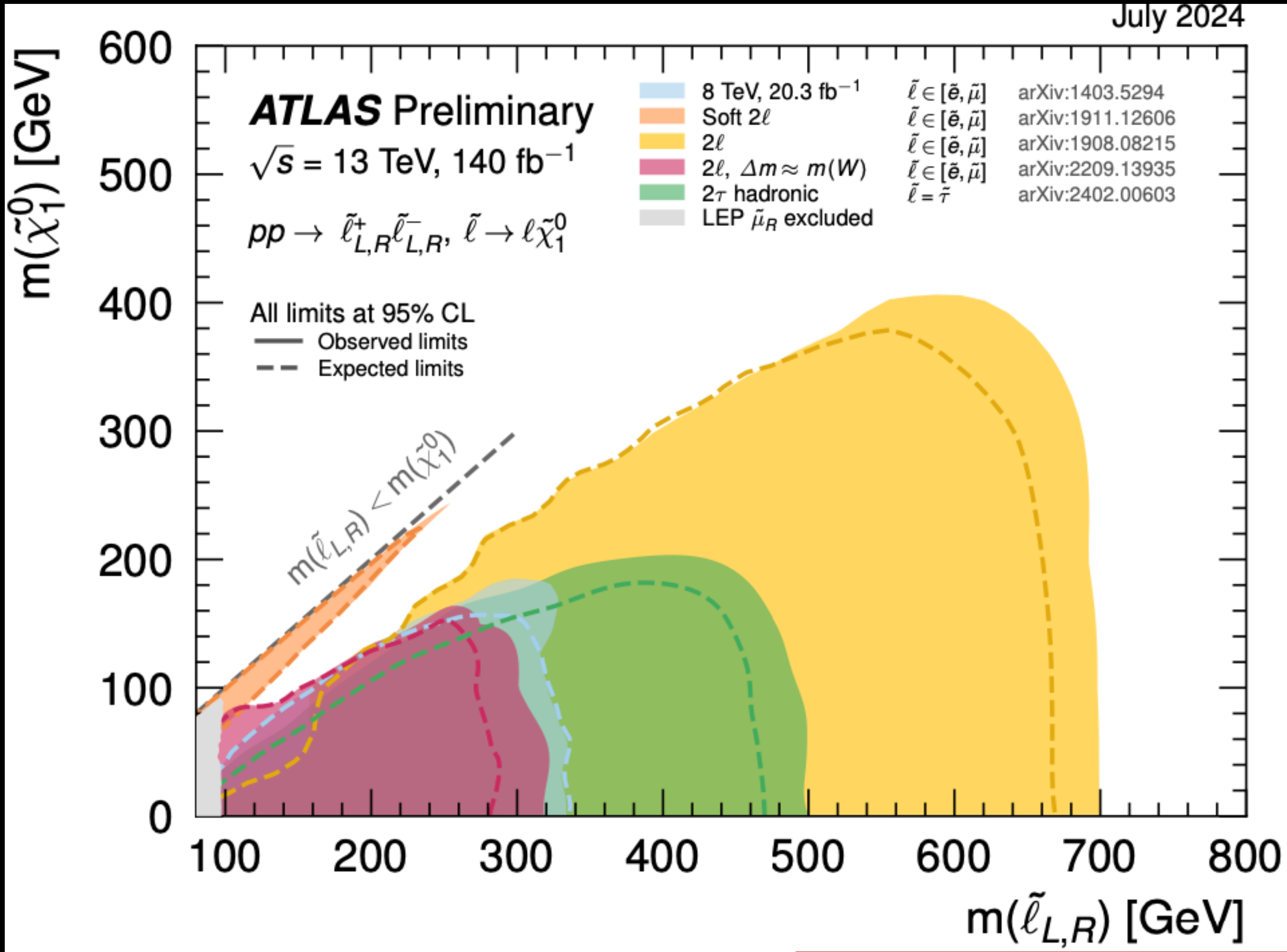
LHC Searches for Neutralinos



ATLAS Collaboration, ATL-PHYS-PUB-014

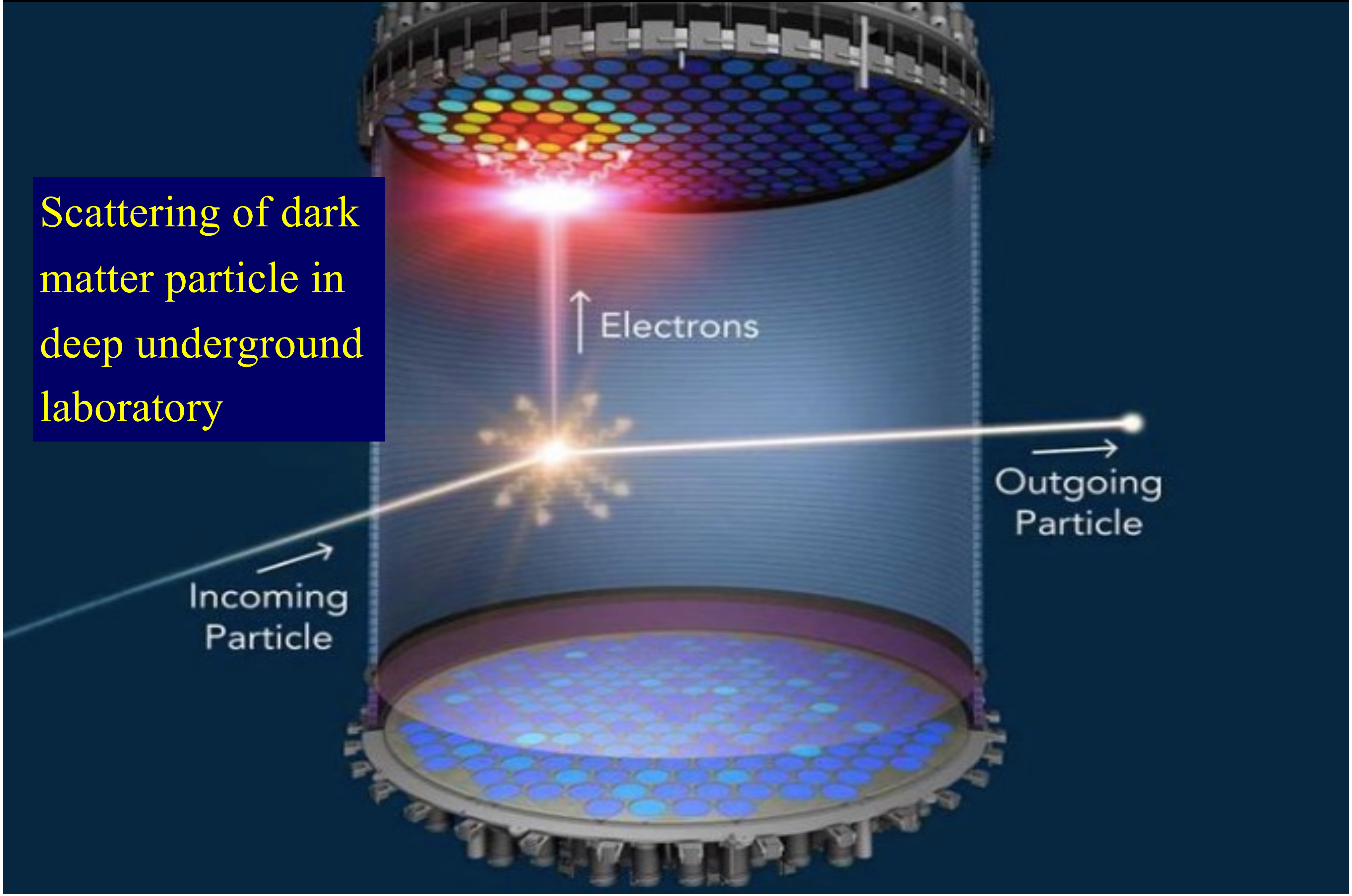
LHC Searches for Sleptons



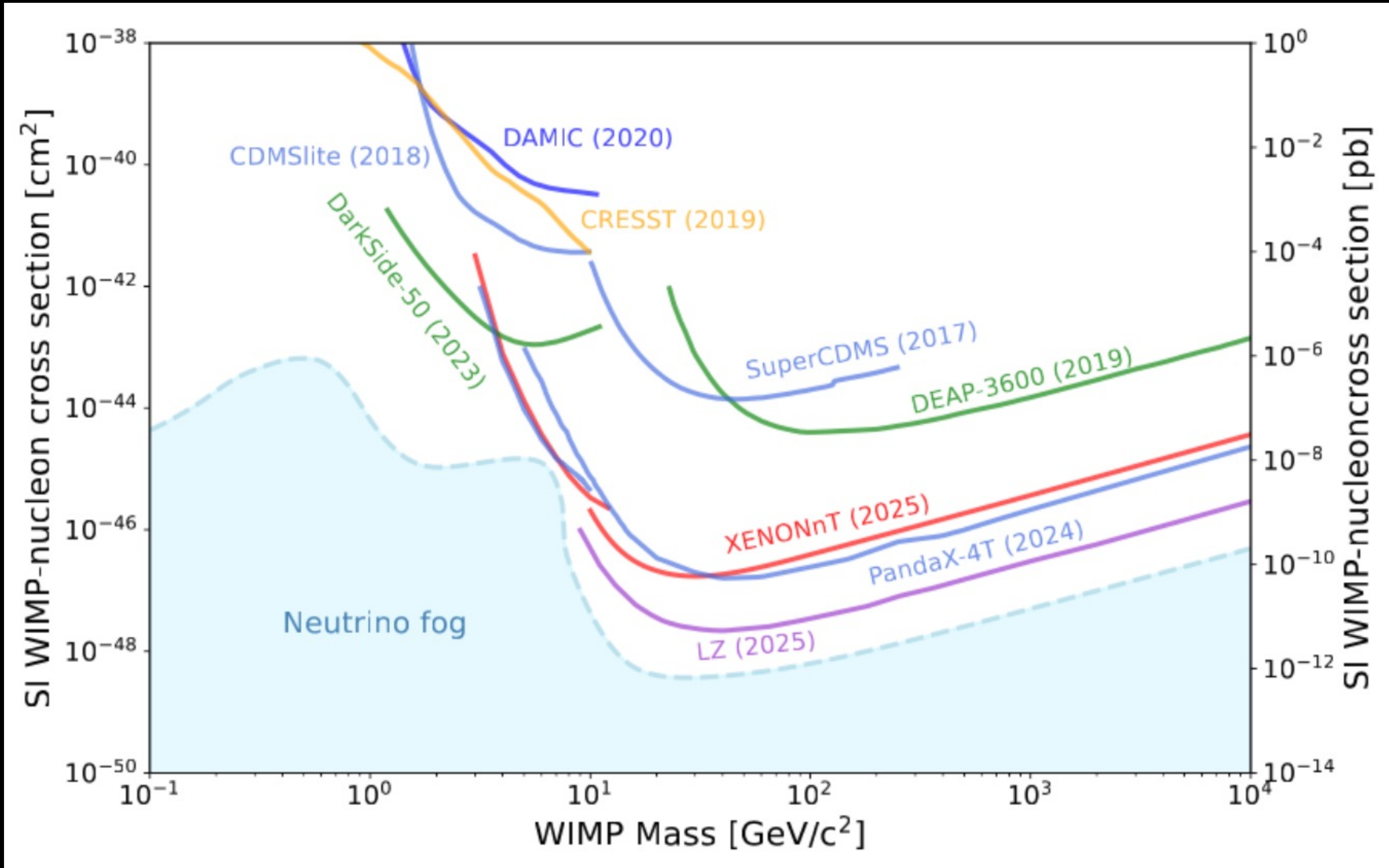
ATLAS Collaboration, ATL-PHYS-PUB-014

Direct Dark Matter Detection

Scattering of dark matter particle in deep underground laboratory

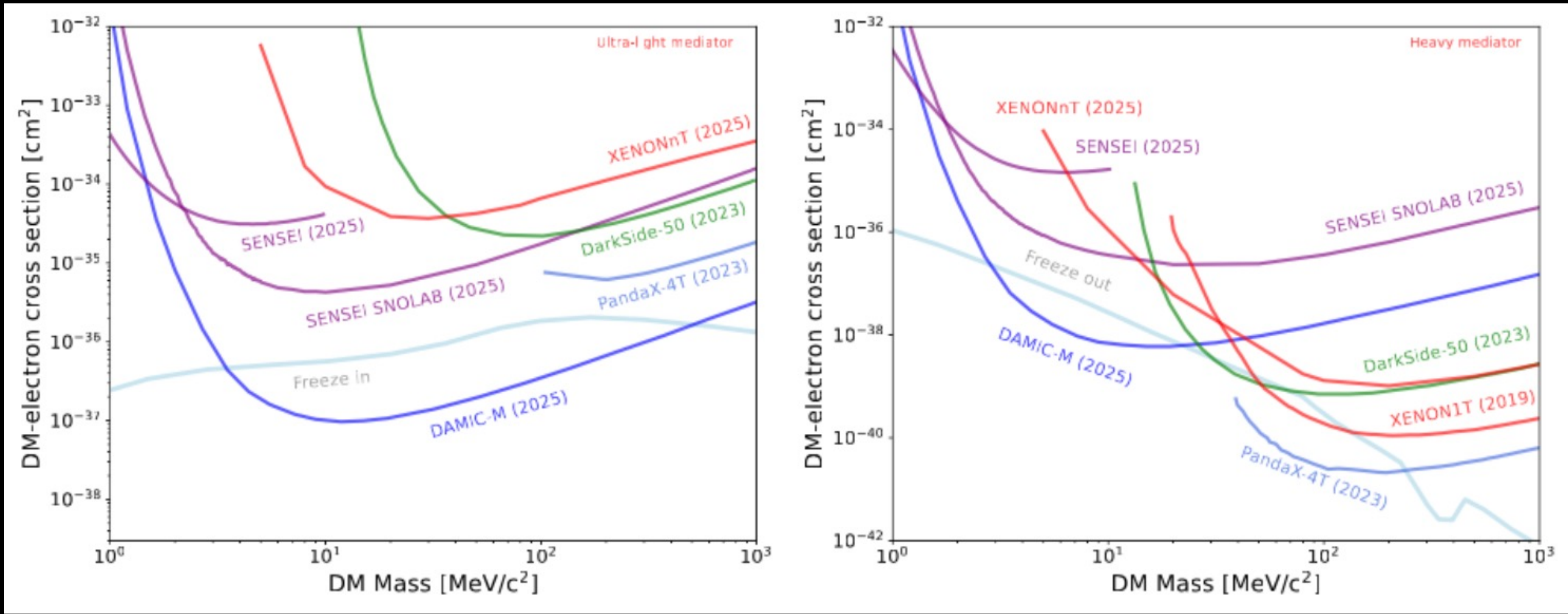


Compilation of Direct WIMP Searches



Particle Data Group

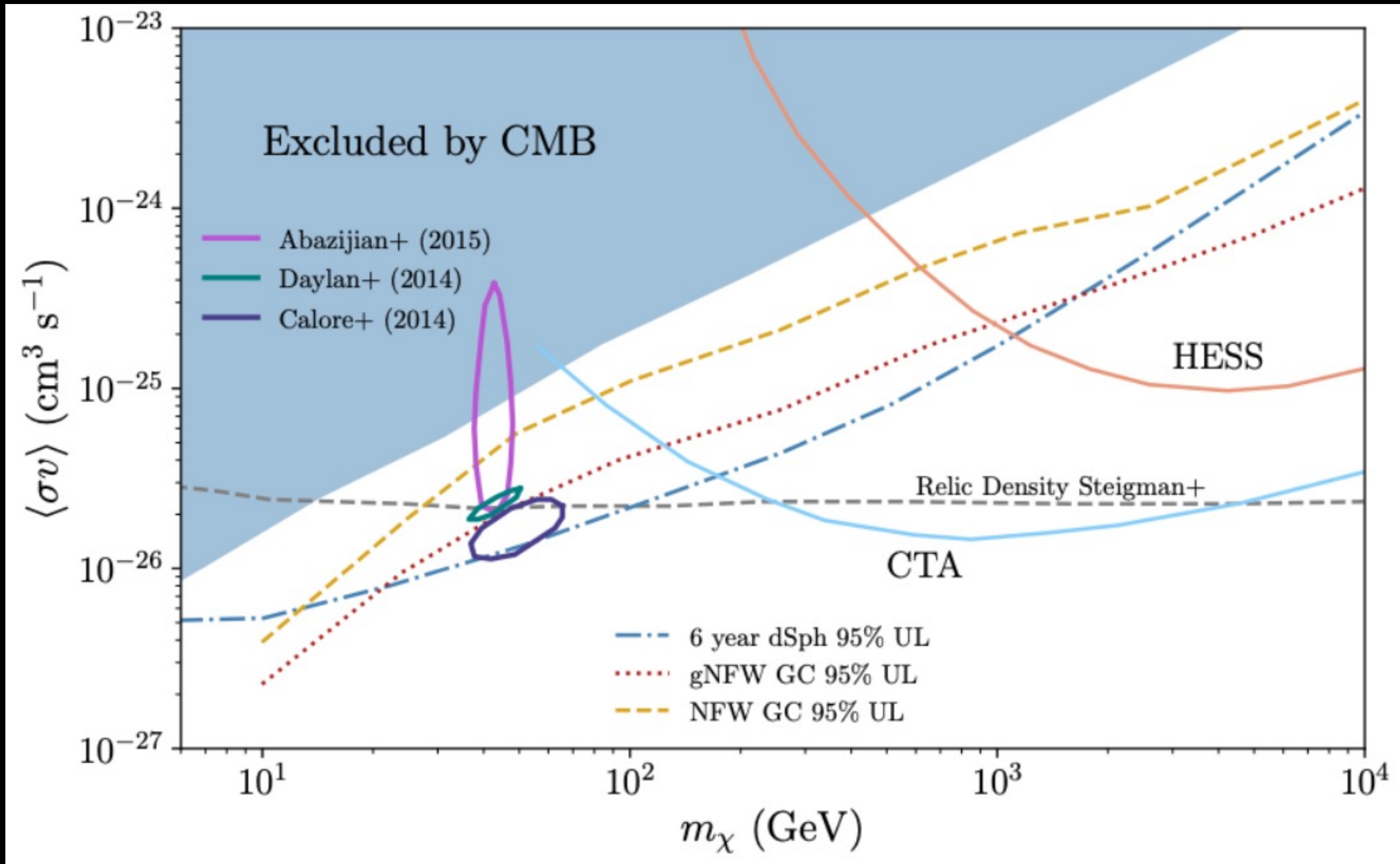
Searches for WIMP-Electron Scattering



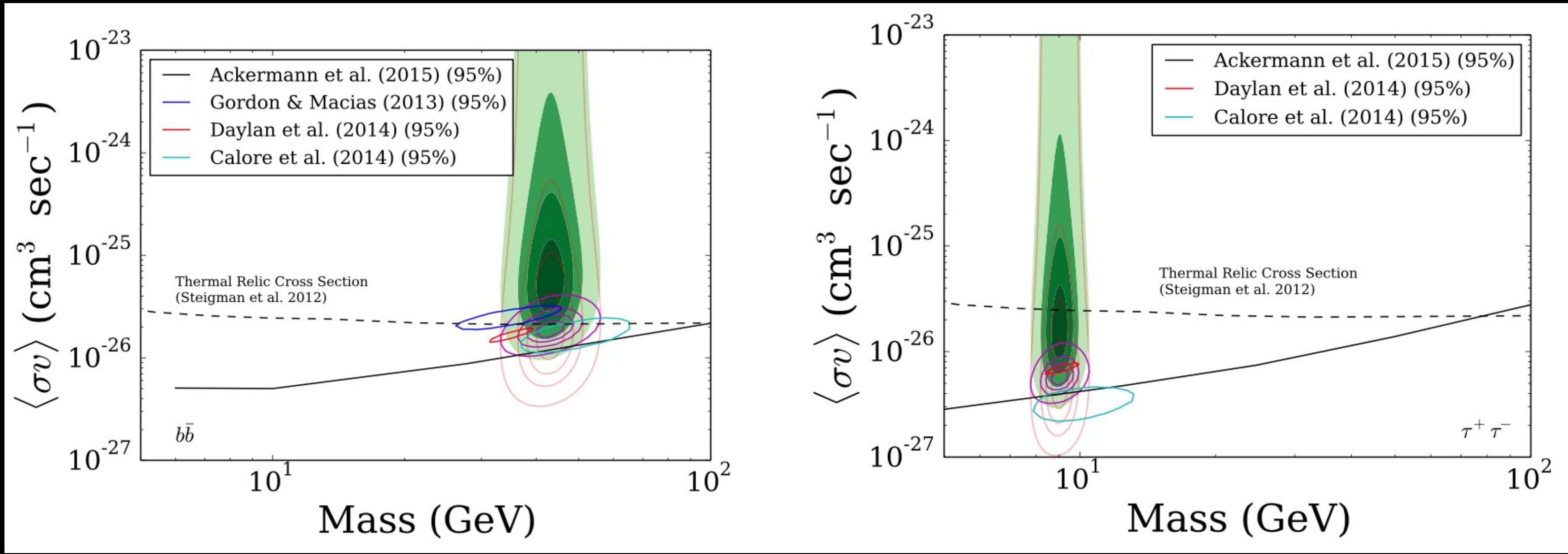
Light mediators   Heavy mediators

Particle Data Group

Indirect Searches for WIMP Annihilations



Indirect Searches for WIMP Annihilations



Annihilation to b + anti-b

Annihilation to tau + anti-tau

Particle Data Group

Challenges for Cold Dark Matter

- Missing satellites
  - Simulations suggest Milky Way should have hundreds of satellite dwarf galaxies, many fewer seen
- Cusp-core problem
  - Simulations suggest density spikes in centres of galaxies, not seen by observations
- Too-big-to-fail problem
  - Masses of halos of satellites smaller than simulations
- Shortcomings of simulations?
- Warm dark matter?
- Self-interacting dark matter?